# PHOTOMETRICAL MEASUREMENTS

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# PHOTOMETRICAL MEASUREMENTS

AND MANUAL FOR

## The General Practice of Photometry

WITH ESPECIAL REFERENCE TO
THE PHOTOMETRY OF

## ARC AND INCANDESCENT LAMPS

BY

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# PREFACE

THE rapid extension of the practice of photometrical measurements in this country, and the general interest in standards of illuminating power and allied subjects evidenced by frequent contributions to the current technical periodicals, and by papers before the various technical and physical associations and societies, have been the occasion for the preparation of this work.

The topical form of discussion has been followed, and a certain amount of repetition has been considered advisable in order to permit concise treatment and definition of the subject matter. In this way, it was thought that the book would prove more useful for reference; and this has been further facilitated by the use of cross-references.

That the work might meet the requirements of a larger number of readers, many topics have been somewhat elaborately and simply discussed which might well have been abbreviated for those conversant with the principles of photometry. And further, in the interest of scientific thoroughness, certain topics have been mathematically treated where this method would lead to definite results capable of ready application; and at the same time, where advisable, collateral paragraphs are given which describe the application of these discussions in order to render the book serviceable as a manual. On the other hand, there are subjects whose mathematical discussion would lend no increased precision to applied photometry, and these have been either briefly indicated or wholly omitted; but where possible, ample references have been stated to enable them to be satisfactorily investigated.

Frequent references will be found accompanying the text. These occur in the discussion of the historical development of the various phases of photometry, and considerable pains have been taken to make these as complete as possible; also the statement, both of fact and conclusion, has so far as practicable been accompanied by references to sources in which the topics are developed at length, preference being given to those which discuss the subjects in an authoritative and thorough manner. The use of copious references has been dictated by a belief that the practical end is best achieved by a thorough mastery of all the details involved, and that the authoritative statement is of slight value which is not based on a complete knowledge of all the phases of the subject at issue.

The common practice of writing manuals and texts without adequate references to the general literature of their subject-matter is reprehensible; while, on the other hand, the impartial method of the exact scientific treatise is one that should commend itself to writers of all but the most elementary texts. Otherwise, the reader must accept the written statement of the author without recourse, resulting in an attitude of dependence and uncertainty. To the general reader, an author may be at times obscure because of the dissimilarity in the attitude with which the subject is approached. This entails needless confusion and loss of time; for, where the author has abbreviated, the reader's general knowledge may be inadequate to follow the text. There are other readers whose needs have been considered, who have neither time nor opportunity to follow references; and these properly desire precise and simple statements which may be readily applied by them.

To those who desire to follow the practice of photometry, and lack an adequate knowledge of general physics, this work may appear too scientific for a manual, and be too insistent on details which apparently have little significance. To such the writer would state that photometry is not a simple and well-defined subject. Bare directions will not suffice, but the

practician must bring to the task a judgment trained for instrumental manipulation and an appreciation of the many modifying influences that the results which he obtains may possess any value.

The work has been written from the literature of photometry and with little reference to existing works on this subject. The references accompanying the text will be found to give a selected bibliography of photometry, and should prove useful both to the investigator and the reader who desires to pursue his study independently. An admirable bibliography of photometry prior to 1884 is given at length in *Die elektro-technische Photometrie* by Dr. Hugo Krüss, in Hartleben's *Elektro-technische Bibliothek.*

The book was originally planned to be written with the collaboration of Mr. Elmer G. Willyoung, who was subsequently prevented from participation in its preparation by other duties. The author is indebted to him for the suggestion of the work and assistance in planning it.

It is with pleasure that acknowledgments are made to my former assistant, Mr. Truman P. Gaylord, for tests and data bearing on the life characteristics of the incandescent lamp; to both the Columbia Incandescent Lamp Company and the General Electric Company for data and the particulars of processes of the manufacture of lamps; and to Queen and Company for illustrations. The author also wishes to express his appreciation of the unusual facilities of the Library of the Franklin Institute, where the preparation for the text was accomplished, and to acknowledge the numerous courtesies extended to him by the secretary and librarian of the Institute.

W. M. S.

SWARTHMORE, PA.,
May 1, 1900.

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# PHOTOMETRICAL MEASUREMENTS

## CHAPTER I

### THE GENERAL PHYSICAL AND PHYSIOLOGICAL PRINCIPLES OF PHOTOMETRY

**1. Photometry** is a branch of scientific measurements which deals with the comparison of the illuminating properties of light sources.

All knowledge of illumination being ultimately obtained through the eye as an organ of sensation, the subject of photometry has a distinctly physiological as well as physical basis, and each must be carefully examined before the intricacies and limitations of such measurements can be investigated.

According to the physical basis of photometry, light in common with heat is a periodic displacement in the ether with resulting waves of exceedingly short periods, which vibrate transversely to their lines of propagation.

**2. On measurement.** — Enlarging upon the similarity between the physical properties of light and heat, an illustration may be taken from the measurement of temperature which may serve as an introduction to the requirements of an instrument which shall be suitable for the exact measurement of the illuminating properties of light sources.

If a mercurial thermometer is placed at any point in a room, it will presently register the intensity of the heat in its locality; and when moved to successive positions about the room

it will afford easy and certain measurement of the relative intensities of the heat in its several locations. As thus used it is a convenient instrument for determining the distribution of temperature about the room.

Carrying the illustration further, should the room be heated artificially, the thermometer placed near the source of heat will presently measure its intensity.

Precisely stated, the thermometer is an instrument designed to measure the intensity of heat, and the thing measured produces a definite physical change in the instrument, a change of the volume of the mercury contained in it. This change of volume is referred to a well-known unit, a degree of temperature, which can be universally applied and reproduced under the standard conditions of the normal freezing and boiling points of water. The sensitiveness, too, of the thermometer may be made very high.

**3. The ideal photometer.** — This discussion affords a criterion for what is desirable in a photometer which shall measure the intensity of illumination as accurately as the thermometer does the intensity of heat. Following out this illustration, suppose a simple and accurate photometer is placed successively at different points in a room lighted by an incandescent lamp, and finally is directed toward the source of light itself. The readings thus obtained would afford not only a precise knowledge of the intensity both of the illumination at points in the room and of the source of light, but also of the distribution of the illumination.

Applying the criterion to the photometer, it is found that such precise measurements become possible only when the luminous property of the light produces on the photometer some physical change whose character is well known and capable of exact measurement.

**4. The eye as a photometer.** — A second illustration may be helpful to a clear conception of the capacity in which the

unaided eye may act as an instrument for measuring, or rather estimating, the intensity of light.

The attraction between the moving magnetic system and the fixed one of a coil carrying a current and deflecting a magnet suspended within it, may be numerically expressed by the general law of attraction,

$$F = k\frac{mm'}{d^2}. \tag{1}$$

What is here emphasized is that the constant $k$ refers to the ability of the medium between the two attracting systems to transmit a definite, mutual-stress disturbance. Should the transmitting power of the medium change from day to day, or, indeed, from hour to hour, and be susceptible to fatigue, galvanometry would become impossible; for the measurements of electric currents made at different times would not be comparable.

In like manner a general visual law may be stated, which shall define the degree of the sensation of a luminous source as a function of its physical intensity. This law may be phrased

$$S = a\frac{P}{d^2}, \tag{2}$$

the symbols referring, $S$, to the sensation; $P$, to the intensity of the source of light; and $d$, to the distance between the eye and the source. The significant symbol is the constant $a$, which connects the sensation with a purely physical relation

$$\frac{P}{d^2}.$$

In reality, what has been attempted in this expression is an equation between a psychological and a physical quantity, the correlation of these two classes of phenomena being affected through the constant $a$.

The eye and its associated neural structures act as the medium in this correlation. Regarding the optical structures

as a mere apparatus they are seen to lack constancy of action and to be subject to the unknown quantitative action of fatigue. The quantity $a$ varies in an irregular manner from time to time, and one can not depend upon it to show successively constant values. Fatigue, nutrition, and the general condition of the nervous system, all have their influence upon it.

To pursue the subject further, — for this is one of the perplexing psycho-physical problems that enter into photometry, — no dependence can be placed upon the memory of an amount of a sensation. Should the quantity we have called $a$ be constant on two successive trials, separated by a short time-interval, as an hour, no one can state with the perfect definiteness of the readings of a galvanometer, that the two light sources viewed in succession were of equal intensity.

Thus no one can depend upon the eye to compare the intensity of one light source with that of another. In these cases the eye is seen to lack the essential requirements for an apparatus for the measurement of the intensity of light.

A much greater complication is introduced when the change of the sensation with respect to the variation of the exciting light source is considered. This phase will be subsequently discussed (page 15).

## PHYSICAL PRINCIPLES

**5. On ether waves.** — Light may be defined for our purpose, as transversely vibrating ether waves, whose frequency of vibration is such that, falling upon the retina of the eye, they produce the sensation of sight. This definition of light is usually termed a subjective, or physiological one, but it is adopted as the most suitable one for the discussion of the principles of photometry.

A wave train is transmitted through the ether by series of successive displacements, which are repeated in all respects in equal but very short periods of time. This may be illustrated by a diagram (Fig. 1). An undisturbed chain of particles, $A$,

$B \cdots O$, is shown, whose members are so elastically connected with each other that one in moving pulls upon its fellow. When the particle $A$ is set into transverse vibration, it communicates a similar movement in succession to $B, C, D \cdots$ and $O$, and the chain vibrates like a stretched string.

After the disturbance has reached the particle $O$, the position of each member of the chain is shown by the points $a, b, c, d \cdots o$. This latter arrangement of the particles illustrates a complete wave form, and a succession of similar wave forms constitutes a *wave train*. The line $XY$ is the axis of the wave, and the distance from $a$ to $o$, denoted by $l$, is the *wave length*. The greatest displacement of the particles from the axis $XY$

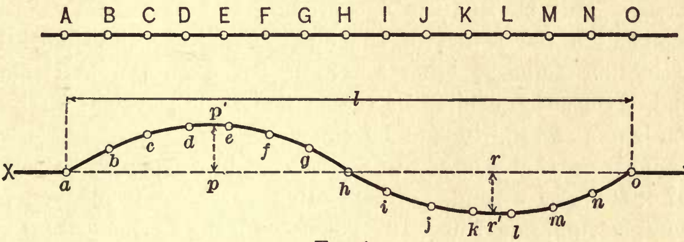


FIG. 1.

occurs at $p'$ and $r'$, and their distance, $pp'$ or $rr'$, from the axis is called the *amplitude* of the wave. The time which is required for the motion of the particle $a$ to reach the particle $o$ is the *period* of the vibration; and the number of times this disturbance is completely repeated in a second is the *frequency*. Such wave trains are propagated through the ether with a definite velocity, and if this is denoted by $v$, the period of the wave by $\tau$, and the frequency by $f$, the length of the wave being $\lambda$, the relations between these various quantities are

$$\tau = \frac{1}{f}, \tag{3}$$

and

$$\lambda = v\tau = \frac{v}{f}. \tag{4}$$

The most accurate determination of the velocity of the propagation of light through a vacuum is not far from 299,860,000 metres per second; this particular value having been obtained by Newcomb at Washington in 1882.*

**6. Visible light.** — The ether waves which produce the phenomena of heat and light are inherently the same, though, in general, the vibrations which are commonly termed heat waves have a much lower frequency than the vibrations giving rise to visible light. It is essential to note that the distinction between heat and light is largely physiological and subjective: the ether waves which excite the sensation of warmth on the body are known as heat waves; while light waves are those having a suitable frequency to produce sight sensations when received on the retina of the eye. Thus the physiological distinction amongst ether waves is based on the particular kind of sensation excited by them; and their physical distinction is one of amplitude and frequency.

Light, or visible ether waves, ranges in frequency between $392 \times 10^{12}$ per second, corresponding to the extreme red of the spectrum, and $760 \times 10^{12}$ per second, the extreme limit of the violet end of the spectrum. These are merely general limits, and are not constant for the same eye nor for different eyes.

**7. The physical meaning of colour.** — In the physical sense the colour of light waves is defined by their particular *pitch* or *frequency;* and one light wave differs from another in colour according as its frequency is higher or lower than that of the wave with which it is compared; and there are as many *physical colours* in the range of visible light as there are possible frequencies between the limits of $392 \times 10^{12}$ and $760 \times 10^{12}$. Yet so closely are the physical and physiological aspects of colour related, that the physical colours are associated into

* See Preston, The Theory of Light, page 505, for a table of the most accurate determinations of this constant.

certain groups corresponding to the manner in which the spectrum of white light affects the eye. If the entire extent of these spectrum groups be represented by a scale divided into one hundred equal parts, the space occupied by each colour group as given by Rood,* is: —

## TABLE I

### Extent of Colour Groups in the Normal Spectrum

| | |
|---|---|
| Red begins at | 00.0 |
| Pure red ends, orange-red begins at | 33.0 |
| Orange-red ends, orange begins at | 43.4 |
| Orange ends, orange-yellow begins at | 45.9 |
| Orange-yellow ends, yellow begins at | 48.5 |
| Yellow ends, greenish yellow begins at | 49.8 |
| Greenish yellow ends, full green begins at | 59.5 |
| Full green ends, blue-green begins at | 68.2 |
| Blue-green ends, cyan-blue begins at | 69.8 |
| Cyan-blue ends, blue begins at | 74.9 |
| Blue ends, violet-blue begins at | 82.3 |
| Violet-blue ends, pure violet begins at | 94.0 |

If the frequency of a colour wave is known at any point of this scale, the corresponding frequency and wave lengths at other points may be calculated by the equations (3) and (4) on page 5. In all cases the length of a light wave is a very small dimension, and for their comparison, a unit length of the one-millionth part of a millimetre may be taken. The grouping of wave lengths by this unit is, according to Rood †: —

## TABLE II

### Wave Lengths in Multiple of $10^{-6}$ Millimetre

| | |
|---|---|
| Centre of red | 700.0 |
| Centre of orange-red | 620.8 |
| Centre of orange | 597.2 |

* Modern Chromatics, or Text-book of Color, O. N. Rood, page 24.

† Rood, reference cited, page 26.

| | |
|---|---|
| Centre of orange-yellow | 587.9 |
| Centre of yellow | 580.8 |
| Centre of full green | 527.1 |
| Centre of blue-green | 508.2 |
| Centre of cyan-blue | 496.0 |
| Centre of blue | 473.2 |
| Centre of violet-blue | 438.3 |
| Centre of pure violet | 405.9 |

**8. Regular and diffused reflection.** — Light rays falling on a surface are reflected, with a certain loss due to absorption, in two distinct ways. Falling on a plane surface, the path of both the incident and reflected rays makes an equal angle with the normal to the reflecting surface. This is variously termed *regular* or *specular* reflection; and its characteristic is, that it produces a glare or an image of the light source in the eye, while the reflecting surface is not visible through such rays. Mirrors and glazed paper, or very white, smooth paper, placed at an angle of 45°, regularly reflect the light in various amounts.

If the surface is rough, the light will be diffused in all directions; and, while no image of the light source is seen, the reflecting surface itself is visible. This is termed either *diffused* or *irregular* reflection.

**9. Selective absorption by reflection and transmission of light.** — Any given set of molecules may absorb the energy of light waves only when there is correspondence between the molecular periods of vibration and the frequency of the light waves. Substances differ widely in their powers of absorption, and to this is due the variety of colour of objects.

When light falls on a surface which absorbs all but the slower light waves and reflects these, the surface will appear red.

Similarly, when white light passes through a layer which is transparent to green rays, and absorbs all other frequencies, the quality of the incident light will be changed to green, after transmission through the plate.

**10. Selective diffusion.** — Closely associated with these phenomena is a third, called selective diffusion. Opal glass owes its peculiar properties to some very finely divided white solid suspended in a matrix of clear glass. The fineness of the suspended particles is comparable to the length of blue light waves, while the particles are too small sensibly to reflect the longer rays of the spectrum. This topic will be further discussed in connection with its application to diffusing screens (page 48).

**11. Total reflection of light.** — When light passes from one medium into a rarer one, the rays are refracted from a normal

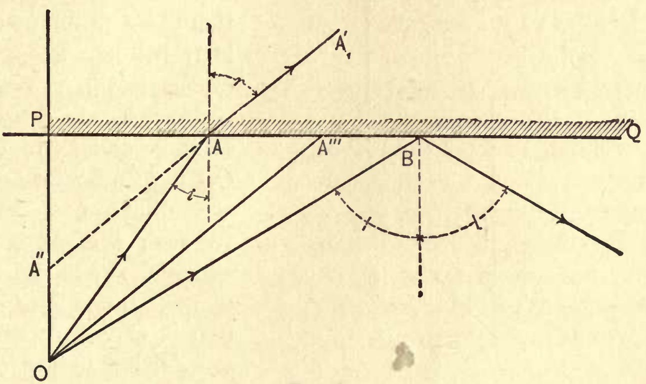


FIG. 2.

to the separating surface. Thus, in Fig. 2, $OA$ is the path of a ray in a dense medium such as glass, whose incident angle to the surface $PQ$ is $i$, and $AA'$ is the path in air refracted at an angle $r$. These angles of incidence and refraction bear a constant relation for any given transparent substance in air, such that

$$\frac{\sin i}{\sin r} = \mu. \tag{5}$$

As the angle of incidence increases, it will eventually attain a value $i'$, such that the ray $OA'''$ will be refracted in the *plane*

*PQ*. This particular value for the angle of incidence is known as the *critical angle* for that substance; and in crown glass, for example, its value is about 40° 30′.

If this critical value is exceeded, the ray of light will not emerge into the air, but be totally reflected back through the glass, as is the case when the ray *OB* makes an incident angle *I* with the normal to *PQ*. The ray then obeys the law of *reflected light*.

One application made of this principle is shown in Fig. 3, which represents a section of a rectangular prism. A beam of light *AO* perpendicularly incident on a face of the prism, is totally reflected at *O*, and emerges along the path *OB* perpendicular to the second face of the prism. In such a case, practically none of the light is dispersed, and its direction is changed without sensible loss in intensity.

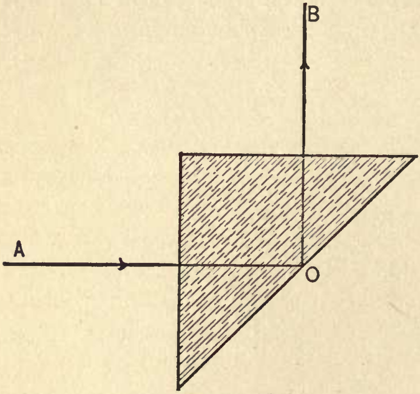

Fig. 3.

**12. Reflection of light from various surfaces.** — The proportion of light reflected from a particular surface depends both upon the angle of incidence and the condition of the surface. The latter is by no means constant in its effect on light; for as a surface becomes rough and soiled by exposure, its reflecting power is proportionately decreased. Data of this character are to be taken as suggestive rather than final. An interesting set of values is given by W. E. Sumpner.* The first four values were determined with great care, the remaining ones are only approximate: —

* Philosophical Magazine; 35, 1893, page 88.

| | Per cent |
|---|---|
| White blotting paper | 82.0 |
| White cartridge paper | 80.0 |
| Tracing cloth, polished side | 35.0 |
| Tracing paper | 22.0 |
| Ordinary foolscap | 70.0 |
| Ordinary newspaper | 50 to 70.0 |
| Yellow wall paper | 40.0 |
| Blue paper | 25.0 |
| Dark brown paper | 13.0 |
| Deep chocolate paper | 4.0 |
| Clean plane deal surface | 40 to 50.0 |
| Yellow painted wall, clean | 40.0 |
| Black cloth | 1.2 |
| Black velvet | 0.4 |

**13. Emissivity, or surface conductivity for heat and light.** — This property enables the superficial layer of a body heated to incandescence, to radiate or pass outward into space both heat and light radiations. If the surface was of such a nature that it would not give out dark heat rays, but pass light rays alone, a condition for ideal illumination would be attained; a condition which is unknown, but which is approached as the temperature of the incandescence of the body is increased.

The hot carbon surfaces of the arc and incandescent lights — aside from the amount of heat lost by conduction to the air and masses in contact — pass the transformed electrical energy and radiate it into space. In the arc light a greater proportion of the energy emitted and radiated produces light waves than in the case of the incandescent lamp, since the temperature is higher.

Again, the emissivity of a surface is to a great extent a function of its character, whether it be hard and bright, or rough and dark. The emissivity of the dull, black carbon filament for both light and heat radiations is greater than that of a brightly polished, flashed surface. In general, polish on a surface lowers its emissivity. The polish imparts greater reflecting power, and more heat and light rays, if the body

is incandescent, are reflected inwardly instead of being radiated outwardly, and their energy is retained.

The *surface emissivity* of a body may be defined as its rate of losing heat or light energy; and it is measured by the quantity of energy lost in one second from unit area of surface, with unit difference of temperature.*

## PHYSIOLOGICAL OPTICS

**14. The physiological meaning of colour.** — A clear understanding of the physiological meaning of colour is necessary to follow the intricacies and difficulties of photometry and standards of illumination. The physiological basis of colour is a particular mode of nerve stimulation in the retina of the eye. This is transmitted to the brain by the optic nerve tract and thence there results a colour sensation. Each kind of colour sensation is probably connected with a definite nerve stimulus. However, it is erroneous to conclude that these definite nerve stimuli are necessarily definitely excited. They are ordinarily excited by ether waves of frequencies already described, yet colour sensation results when the optic nerve tract is excited by an electric current, and by mechanical shock, or pressure. Nor is a particular kind of colour sensation excited only by ether waves of frequencies corresponding to that colour in the spectrum; as an instance, a red colour sensation is induced in varying degrees by practically all the frequencies of visible ether waves.

**15. The Young-Helmholtz theory of colour vision.** — The compound character of white light is shown by spectrum analysis, and it is reasonable to suppose that the colour sensation corresponding to white light is not a simple sensation, in that it is due to one special mode of nervous stimulus. Careful experimentation has established the correctness of this supposition. By means of the rotation of coloured sectors, so rapidly that

* Consult Preston, Theory of Heat, pages 442 and 460.

the excitation of the first sector persisted until the eye was affected by the colour of the last sector, thus superposing the colours of all the sectors, Maxwell showed that the sensation of white light could be produced by a variety of combinations of colours. Finally it has been shown that the sensation of white light may be obtained by the rotation of three sectors, representing three of the principal colour bands of the spectrum in certain proportions,—red, green, and violet. Extending the same method of investigation, Maxwell was able to produce practically the entire range of colour sensations, by varying the relative areas of the red, green, and violet sectors.

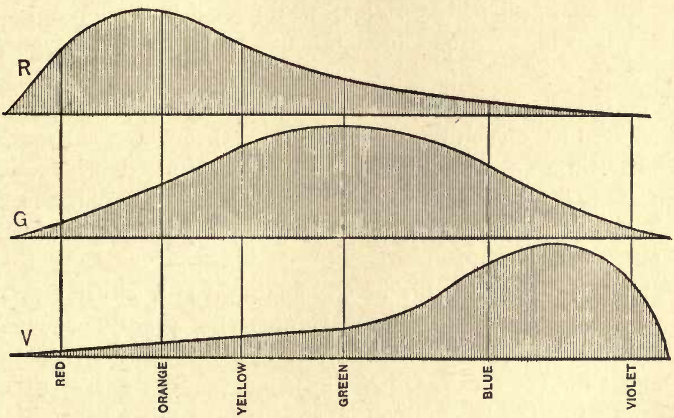


FIG. 4.

In 1802 Thomas Young * published a theory of colour vision, which supposed the retina of the eye to be primarily sensitive only to red, yellow, and blue light stimuli. Subsequently he adopted red, green, and violet as the primary colours, and this latter selection of colours is still adhered to by the advocates of this theory. Later on this theory received such careful experimental exposition through the investigations of Helmholtz and Maxwell, that it is generally accepted as a satisfactory working hypothesis for the phenomena of colour vision.

* Philosophical Transactions, Part I, 1802, page 21.

The Young-Helmholtz theory, as it is now called, is usually discussed by the aid of a diagram due to Helmholtz,* and shown in Figure 4. The curves $R$, $G$, and $V$, refer to the relative intensities of the primary colour sensations of red, green, and violet. It is seen from this diagram that the red primary colour sensation is excited in varying intensities by practically all the frequencies of the visible spectrum, as is also the case with the green, and violet primary colour sensations.

Any given colour sensation is thus a compound one; for example, a yellow is due to a strong excitation of the green primary colour sensation combined with a certain degree of the red, and less of the violet; while for a blue colour sensation, the primary violet predominates with less of the green and red.

The criterion for *normal white light* is, accordingly, a light which will have such relative intensities throughout the length of its visible spectrum that it will excite the primary colour sensations in the ratios indicated in the Helmholtz diagram, or a similar one, should this not be found to represent the normal action of average eyes.

Though our knowledge of the anatomy and physiology of the eye neither confirms nor refutes this theory of colour sensations, the conclusions arrived at concerning white and coloured lights are founded on experimental evidence, and they can not be seriously modified whatever theory may be adopted. This is the sense, that of a working hypothesis, in which the Young-Helmholtz theory of colour vision will be referred to in subsequent portions of this work.

**16. Quantitative judgments of light.** — The question naturally arises in such discussions, Does the intensity of a sensation bear any relation to the magnitude of its stimulus? For illustration, suppose two incandescent lights be looked at in succession in such a manner that the eye receives no light

* Helmholtz, Physiolog. Optik, page 291; also consult Ladd, Physiological Psychology, page 339; and Foster, Physiology, page 899.

not coming from one source or the other. These lights are similar in colour, and one is $n$ times as bright as the other. Will the sensation in one case be $n$ times as intense as in the other?

Again, it must be recognized at the very outset that sensations are eventually psychological, and though received through material agencies, are themselves neither matter nor energy. Under such conditions it is to be anticipated that sensations are not rigidly subject to quantitative expression, as are all relations of matter and energy.

**17. Proposed law of the intensity of sensations.** — This subject has been investigated by exhaustive experiments by Fechner, Weber, Helmholtz, and others; and though a law rigidly adhered to has not been discovered, yet the intensity of normal sensations has been found to follow somewhat closely a relation known as "Fechner's Law."

**18. Fechner's law.** — The simplest statement of this law is that *the differences in sensations vary as the logarithm of the ratio of the stimuli producing the differing sensations.*

If the strength of the sensation was *directly* proportional to the excitation, a light $A$, which is twice as strong as a similar light, $B$, would produce a sensation $a = 2b$, and the mind could in general form fairly accurate judgments of the relative intensities of lights. But the actual relation between the strength of the sensation and its stimulus being so complex, the resulting judgment is confused, and comparisons of the intensity of illumination by the unaided eye are entirely unreliable. This is an essential reason for confining the photometrical measurements of illumination to the comparison of equally lighted fields.

**19. Mathematical discussion of Fechner's law.** — On the supposition that a definite relation exists between the strength of a sensation and its stimulus, if the strength of the sensation be denoted by $S$, and of the stimulus by $I$,

$$S = f(I). \tag{6}$$

It has been experimentally established that the smallest distinct change which the average trained eye can distinguish in the illumination of an object is about one part in one hundred.* This ratio seems to obtain over quite a range of light sensations, and if the illumination be expressed in candle-power units, it would be:

| Total Illumination | Least Observed Change |
|---|---|
| 10 candles | 0.1 candle |
| 20 " | 0.2 " |
| 50 " | 0.5 " |
| 100 " | 1.0 " |

The essential fact to note in such a series of values is that the least observable change of the illumination is not a *constant difference* of candle power, but that it forms a *constant ratio* to the total impressed illumination.

Assuming that the least possible change $\Delta I$ in the illumination $I$, which the eye can detect is, within a certain range, the one-hundredth part of the impressed illumination, the assumption may be given the statement,

$$\frac{\Delta I}{I} = 0.01. \tag{7}$$

The significance of this constant quantity is that the illumination changes in each case by a fixed part of itself.

Denoting the corresponding change in the sensation $S$ by $\Delta S$,

$$\frac{\Delta S}{A} = 0.01, \tag{8}$$

$A$ being used as an equating constant between the change of sensation and its correlative change of stimulus. Then

$$\frac{\Delta S}{\Delta I} = \frac{A}{I}. \tag{9}$$

* Ladd, Physiological Psychology, page 366 and Chapter V; and Helmholtz, Physiolog. Optik, pages 312–316.

By an extension of this method it follows that the stimulus-rate-of-change of the sensation in the last equation is, for all values of the changes in $S$ and $I$,

$$\frac{\delta S}{\delta I}=\frac{A}{I}. \tag{10}$$

Then for exceedingly small changes in $S$ and $I$,

$$ds=A\frac{dI}{I}, \tag{11}$$

and by integration,
$$S=A\log I+c, \tag{12}$$

which determines the relation between the quantity of a sensation and that of its stimulus provided the constants are known.

The law of the *difference of sensations* is of greater interest in this connection. This law may be derived from the last equation by writing in succession,

$$S_2=A\log I_2+c, \tag{13}$$

and
$$S_1=A\log I_1+c; \tag{14}$$

and by subtraction,
$$S_2-S_1=A\log\frac{I_2}{I_1}. \tag{15}$$

**20. Complementary colours.** — Aside from any theory of colour vision, it is an interesting experimental fact that the colour sensation of white light may be produced by various combinations of only two colours. Such colour pairs are, among others, red and very greenish blue; yellow and ultramarine blue; and greenish yellow and violet.*

**21. Fatigue of the eye.** — A peculiar psychological phenomenon occurs through fatigue of the eye after looking at a brightly illuminated object. If a red surface has been looked at intently for some time, and the eye then turned to a white or gray surface, instead of showing in its proper colour, it

* Helmholtz, Physiolog. Optik, page 277.

appears to be greenish blue. Similarly, through fatigue, an orange surface will produce a blue after-colour, and yellow an indigo blue.*

Such phenomena are not without importance in photometry, and in the comparison of lights of different colours are a possible source of confusion and error.

22. **Exaggerated contrast.** — If alternate strips of white and black be looked at closely, the edges of the white strips will appear much brighter by contrast with the black than their central portions. The judgment of the intensity of the illumination, formed under such conditions, would be out of proportion to the real stimulation of the eye.

In the preceding paragraph it was explained that complementary colours were seen by successive contrast — the eye being moved from one surface to another. But such phenomena of complementary colours may occur by simultaneous contrast, though in a lesser degree. If lights of different colours are brought together on a surface, the edge of each will not appear in its true colour, but be blended to some extent with its complementary colour. This confusion disappears when the two colours are separated by a narrow band of black.

A thorough comprehension of the foregoing facts of fatigue and contrast is needed to follow the theory of such screens as the Lummer-Brodhun.

23. **Proper conditions for comparing lights.** — The influence of fatigue in producing complementary colours and exaggerated contrast alone renders accurate estimations of relative brightness practically impossible. By reducing photometrical measurements to cases of comparison of lights of similar colour and equal intensity on the observing screen, such disturbances are almost wholly avoided.

24. **The effects of the persistence of vision.** — If repeated stimuli succeed each other *within* their period of persistence,

* Foster, Physiology, page 934.

the sensation which they will produce is that of continuous light. When the interval between the stimuli is very nearly equal to the time of dying away of a sensation, the light will appear to "flicker." This principle is made use of in the "Flicker" photometer.

If the interval between successive stimuli is distinctly longer than the period of persistence, the light will appear intermittent. Experimental data show that when the stimulus interval is shortened, the intermittent light appears flickering and finally continuous, and that the particular interval which marks the passage from a flickering to a continuous light sensation is, for weak light and the average eye, about $\frac{1}{10}$ second, and for very strong light $\frac{1}{24}$ second.* These principles are also employed in the rotating sector disk.

**25. Illumination.** — This is a subject over which many obscurities and errors of photometry have originated, and precision in photometrical measurements requires a clear comprehension of the elements which enter into the definition of illumination. The term may be provisionally defined as the quality and quantity of light which stimulates the eye in discrimination of outlines and perceptions of colours; and emphasis is laid upon both the qualitative and quantitative aspects of illumination.

Here again the primary fact is psychological, — the *light sensation*, — and one must proceed outward through the physiological excitation of the retina, to the physical disturbances producing it.

The influence of the quantity of light is defined by Fechner's law, yet, at the basis of a satisfactory definition of illumination, is that certain amount of light which is requisite for clearly and easily seeing the outlines of objects. To this must be added the proper quality of light to bring out the colours of objects.

* Helmholtz, Physiolog. Optik, page 345.

**26. Physical basis of illumination.** — Primarily, illumination refers only to the light reflected to the eye from surrounding objects, yet for brevity it can be taken to include as well the source of light. The luminous source may give out either simple or complex light. Light is simple when it consists of waves whose frequencies lie within one colour group alone. The yellow light from an alcohol flame with sodium chloride in solution is nearly monochromatic.

Except in such special cases the quality of an illumination is complex, containing all or a part of the colour groups of the spectrum in varying amounts.

In addition to the frequency of each wave train, the amplitude of its vibration is significant. By reference to Figure 1, the physical basis of illumination is seen to be a function of the wave length $\lambda$, and the amplitude $pp'$ of its vibration.

If the experimental data are accepted as a standard from which the curves shown in Figure 4 were platted, *normal illumination* may be defined as that combination of frequencies and amplitudes which will excite the primary red, green, and blue colour sensations to the extent there indicated.

**27. The perception of colour.** — It has already been pointed out in what sense a source of light may produce colour sensations. The colour sensations derived from non-luminous objects, however, are not produced so simply. In all such cases the illumination is due to reflected light, and in this process the character of the light undergoes more or less change.

A white surface reflects practically all the visible wave frequencies which fall upon it from any source of light whatever. A coloured surface, on the other hand, suppresses certain frequencies and reflects others; a red surface absorbs practically all wave frequencies but those corresponding to the red colour groups, which it reflects. Normal light falling upon such a surface is partially absorbed and partially reflected, while a simple incident light, such as violet or yellow, is prac-

tically absorbed and the surface appears almost black. The illumination of *non-luminous* objects then, being due to reflected light, they require for full illumination that the incident light shall contain all those wave frequencies which they can reflect, and that the amplitude of the reflected waves shall be sufficiently great normally to excite appropriate primary colour sensations of the eye.

**28. The duration of the light impression upon the retina.** — An illumination impressed upon the retina, whether it is weak and continued for a long time, or very intense and for an exceedingly short period, like that of an electric spark, produces a light sensation which persists for a time after the cause has ceased to operate. The phenomenon is one of much practical importance in photometry and must be investigated in its details to determine in what degree the length of the period of persistence is a function of the colour, the intensity of the illumination, and the length of the exposure of the retina to it.

These details have been carefully studied by Nichols * and Ferry.† They have found that the duration period shortens with an increase of the intensity of the illumination exciting the retina, and attains a fairly constant minimum value for a certain intensity beyond which it does not measurably lessen.

The term "duration period" is not fully explicit. It defines the length of time over which the sensation of light remains sufficiently strong not to cause a rhythmic variation when an illumination is viewed through a sectored disk, rotating at a critical speed for the particular conditions prevailing. The total duration greatly exceeds this, for such impressions apparently die away by an approximately logarithmic decrement.

For the duration period as a function of the intensity of the illumination, Ferry has obtained the values: —

* E. L. Nichols, American Journal of Science; 28, 1884, page 243.

† E. S. Ferry, American Journal of Science; 44, 1892, page 192.

| Wave Length | Duration in Seconds | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 4 | 8 | 16 | 24 |
| 0.540 | 0.0200 | 0.0192 | 0.0172 | 0.0156 | 0.0133 | 0.0199 |
| 0.589 | 0.0170 | 0.0161 | 0.0147 | 0.0132 | 0.0102 | 0.0081 |
| 0.684 | | 0.0238 | 0.0217 | 0.0192 | 0.0172 | 0.0156 |

The duration period as a function of the colour of the illumination, or its prevailing wave length, according to Nichols'* experiments, for the brightest illumination with which he experimented, but whose intensity is unfortunately not stated, is: —

| Colour and Wave Length $10^{-7}$ Millimetre. | Persistence Interval | Length of Exposure |
|---|---|---|
| 7420 (red) | 0.0769 seconds | 0.00209 seconds |
| 6463 (orange) | 0.0641 " | 0.00175 " |
| 6025 (yellow) | 0.0523 " | 0.00144 " |
| 5415 (green) | 0.0690 " | 0.00188 " |
| 4784 (blue) | 0.0860 " | 0.00234 " |
| 4382 (violet) | 0.1072 " | 0.00286 " |

To determine the extent to which the duration period was a function of the length of exposure of the retina to the exciting light, the same investigator, employing a gas flame as a light source, found the values: —

| Exposure of the Retina | Duration of the Image |
|---|---|
| 0.0124 seconds | 0.0954 seconds |
| 0.0274 " | 0.0824 " |
| 0.0717 " | 0.0717 " |
| 0.1314 " | 0.0654 " |
| 0.2316 " | 0.0463 " |
| 0.4506 " | 0.0409 " |
| 0.7566 " | 0.0327 " |

* Nichols, ref. cit., page 247.

"The effect of stimulating a 'red,' 'green,' or 'violet' nerve is always the sensation we call red, or green, or violet, as the case may be, no matter what the nature of the stimulating agent, and the varying duration of colour impressions is due primarily to variations in the rapidity with which these nerves recover from the action of the impinging ray. Of the three primary colour sensations, green is the most transient and violet the most persistent. Upon this supposition, whatever may be the predominant tint of a ray of light under ordinary circumstances, the final impression, after the ray has ceased to act, will be one of violet.

"The general conclusions to be drawn from these experiments are: —

"(1) The persistence of the retinal image is a function of the particular wave length producing it, being greater at the ends of the spectrum and least in the yellow rays.

"(2) It *decreases* as the intensity of the ray producing the image increases.

"(3) The relative duration of the impression produced by the different spectral colours is not the same for all eyes.

"(4) The duration of the retinal image is in inverse order to the length of exposure to a particular source of illumination." *

**29. Talbot's law.** — This very simple principle of intermitting the illumination, and diminishing its apparent intensity without affecting its quality, was stated by Talbot † in 1834. It is practically the same principle employed by Maxwell in his rotating disk.

Accordingly, when by any suitable mechanical means, the light falling on a surface is periodically cut off for a very short time with a frequency which prevents the eye from becoming conscious of the alternations, the effect on the eye is equivalent to a proportionate decrease of the illumination. ‡

* E. L. Nichols, ref. cit., page 252.

† Philosophical Magazine; 5, 1834, page 327.

‡ Ladd, Physiological Psychology, page 473.

**30. The rotating sector disk.** — This principle is readily applied in the transmission of light by a rotating disk from which a sector has been cut out for the passage of the light. The disk must be rotated at such a speed that it will make a complete alternation within the time limit of the persistence of vision. Ladd * places this at less than 0.04 second. If $n$ is the angular opening of the sector for the passage of the light, the illumination $I$ will be apparently reduced to a value $I'$ such that

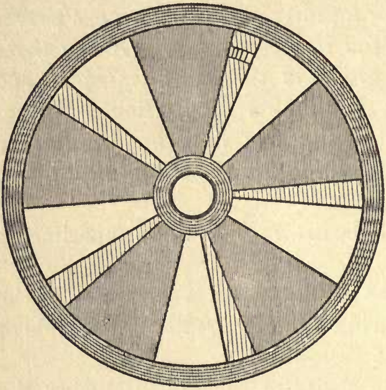

FIG. 5.

$$I' = \frac{n}{360} I. \tag{16}$$

Or, in case the disk (Fig. 5) is perforated with a number of sectors, if $s$ is the area of the openings and $S$ the whole area of the disk zone, then

$$I' = \frac{s}{S} I. \tag{17}$$

Such a device is preferable to one which diminishes the light by absorption, for it does not affect the quality or diminish its intensity, and while it alters the total amount of energy falling on a surface in a given time, the effect of diminished sight sensation is wholly physiological and due to an integrating action of the eye.†

* Ladd, ref. cit. For time of distinct vision, consult Langley, American Journal of Science; 36, 1888, page 359.

† For an excellent discussion of the application of the Talbot principle, see article by Lummer and Brodhun, Zeitschrift für Instrumentenkunde, 1896, page 299.

Ferry * has shown the limits within which the Talbot principle obtains, and has found values for the error in all other cases liable to occur in practice.

The relations pointed out by the equations just stated are physically true whatever the ratio of the aperture to the disk $\frac{s}{S}$, may be. But the decrease of the physiological disturbance is not a linear function of the time, but the disturbance dies

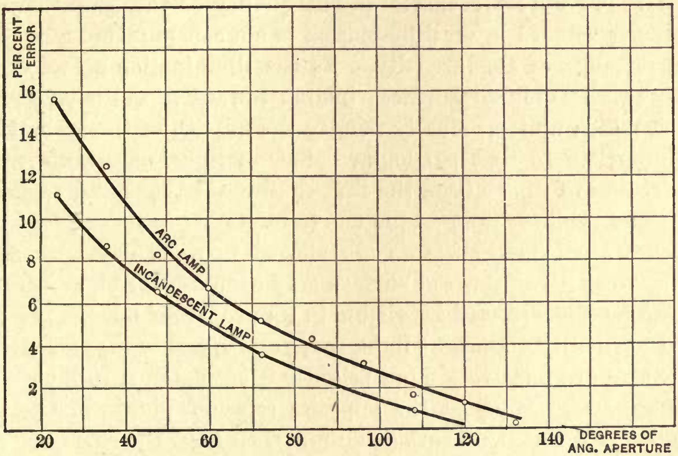


FIG. 6.

out somewhat like damped vibrations. When the angular aperture of the disk exceeds 180 degrees the error in applying Talbot's principle is negligible, but when it is less than 180 degrees the error becomes appreciably greater as the aperture is diminished, until for 24 degrees it is 15.6 per cent for the arc light and 11.3 per cent for the incandescent lamp. The variation of the error with the aperture is platted for each light in Fig. 6. It is seen that the magnitude of the error is affected by the quality of the light through the greater persistence of

* Physical Review, Vol. I, 1893, page 338.

the more energetic waves of the less luminous end of the spectrum.

*In practice* the errors due to these complications may be made inappreciable by not attempting to cut off more than one-half the incident light. The disk should be rotated at a speed that will produce apparently uniform illumination of the screen; and any excess above the critical speed for attaining this has no influence on the photometrical readings.

**31. The Purkinje effect.*** — The quality of the sensation of colour produced by an illumination is not constant throughout a great range of its intensity. As the illumination grows very bright, all coloured surfaces incline toward a whitish yellow tint, which must gradually modify the quality of the sensation appropriate to that particular colour of light. Purkinje and Dove seem to have been the first to discover that a red surface appears brighter than a blue one in daylight, while the reverse occurs when these surfaces are viewed in weak daylight. In very weak light the red surface may even appear black, while the blue one will still be visible in its proper colour.

In general, in a bright light, red, yellow, and orange-coloured surfaces are relatively more brightly illuminated than blue and violet ones, while just the opposite relations obtain in a weak light. All colour sensations do not then have the same law of the variation of intensity, but each has a different value for its rate of change, which is much greater for red than blue illuminations.

The Purkinje effect is one which must be guarded against in photometry, except when normally white illuminations are viewed. In case a white screen or surface is illuminated from a light source of yellowish tint, this tint will be pronounced when the surface is brightly illuminated; while, if the illumination becomes especially weak, the surface may assume a bluish tint.

* Purkinje, Physiologie der Sinne, Vol. II, page 109; and Rood, Modern Chromatics, page 189; and Helmholtz, Physiolog. Optik, page 317.

This is not without an influence on the setting of the screen. If light sources of a red or yellow, and a blue tint, as an amyl acetate flame and an arc light, are compared under the conditions of a brightly lighted screen, the photometer setting will show a relative advantage in favour of the red or yellow source. Should the lights be more widely separated until the illumination of the screen becomes perceptibly weak, the intensity of the blue light would be unduly emphasized.

# CHAPTER I

## PHOTOMETRICAL QUANTITIES

### DEFINITION OF FUNDAMENTAL RELATIONS

**32. Photometrical quantities** are developed from the necessity for assigning dimensions to the physical relations involved in any attempt at the comparison or definition of the illuminating power of light sources. These quantities primarily deal with the quantity of light, and the distribution of its intensity along radii vectores, from a luminous source.

Luminous sources themselves will be considered in this work as either primary or secondary: a primary source being one which radiates luminous energy directly transformed within it as the result of the high temperature of the source; while a secondary source is one which reflects radiant luminous energy received upon it, or diffuses the energy passing through it.

**33. Vector distribution of illuminating power from a primary source.** — For the present discussion a primary source of light will be taken to be a luminous sphere whose radius is negligibly small compared with all distances at which the intensity is measured; it may be regarded as a point from which the light rays emanate with equal intensity along each radius vector.

If about this point as a centre, at desired radial distances, concentric spherical surfaces are supposed to be generated, each such spherical surface will normally cut all the rays emanating from the luminous source; and the total light flux will be the same across each surface.

Considering two such spherical surfaces $S_1$ and $S_2$ (Fig. 7) with radii of $r_1$ and $r_2$ metres, their respective areas will be,

$$\text{Area of } S_1 = 4\,\pi r_1^2 \text{ square metres,} \tag{18}$$

$$\text{Area of } S_2 = 4\,\pi r_2^2 \text{ square metres.} \tag{19}$$

The same quantity of light $Q$ falls on each surface; and, accordingly, denoting the quantity of light for each square metre on $S_1$ and $S_2$ by $q_1$ and $q_2$,

$$q_1 = \frac{Q}{4\,\pi r_1^2}, \tag{20}$$

and
$$q_2 = \frac{Q}{4\,\pi r_2^2}. \tag{21}$$

Consider further an area of $m$ square metres on each spherical surface: the quantities of light falling on these areas from the common source will have the relation,

$$\frac{mq_1}{mq_2} = \frac{4\,\pi r_2^2}{4\,\pi r_1^2} \tag{22}$$

or
$$\frac{q_1}{q_2} = \frac{r_2^2}{r_1^2}. \tag{23}$$

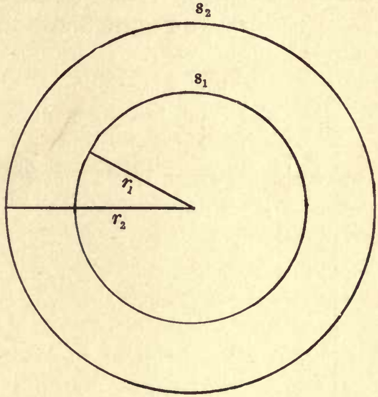

FIG. 7.

Should the light not fall normally on the spherical areas involved but at an angle $\theta$, between the normal to each surface and the path of the light rays, the quantity of light $q$ will be,

$$q = \frac{Q}{4\,\pi r^2}\cos\theta, \tag{24}$$

while between two parallel surfaces $mq_1$ and $mq_2$ there will still obtain the relation: —

$$\frac{q_1}{q_2} = \frac{r_2^2}{r_1^2}. \tag{23}$$

In general, then, whatever may be the geometrical character of areas illuminated from the same source, so long as they are parallel each to each, the relations just established may be shown to hold true for them.

**34. The fundamental law of distances.** — A general law may be derived from these geometrical principles, whatever may be the properties of the luminous source so long as it is practically a radiant point; expressed in words, equation 23 reads, *The quantity of light falling on a given surface varies inversely as the square of the distance from the source.* The working equation derived from this statement will be formally discussed in a subsequent topic (page 32). The geometrical relations are clearly shown in Figure 8, for a source of light placed at $L$.

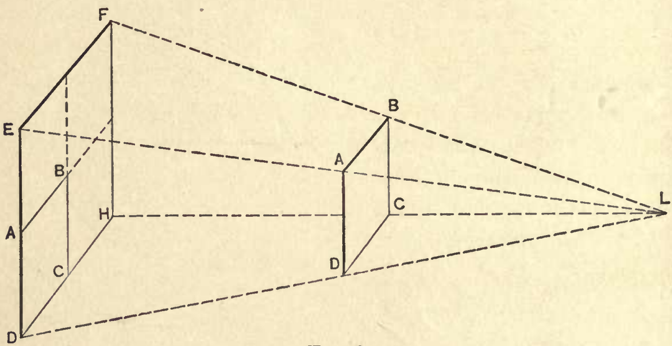


FIG. 8.

**35. The intensity of illumination.** — In order to establish a general statement of this fact, it is seen from the equation, $Q$ being the total quantity of light emitted by the source at a distance $r$,

$$q = \frac{Q}{4\pi r^2}, \tag{25}$$

that when $q = 1$ with unit radius,

$$Q = 4\pi. \tag{26}$$

From these equalities, a definition may be derived which will state the intensity of illumination received on a surface in terms of a *unit of light.* According to equation 26 when the radiant strength of the light source is $4\pi$ units of quantity of

light, a square metre of the concentric spherical surface will receive the unit quantity of illumination, and a light source of $4\pi m$ units of quantity of light will produce on such a surface a quantity of illumination of $m$ units. *The quantity of illumination on the surface at unit distance is then the measure of the illuminating intensity of the light source.*

If the intensity of illumination is denoted by $I$, the quantities $Q$, $S$, and $\theta$, being taken as above,

$$I = \frac{Q}{S}\cos\theta, \tag{27}$$

which is the fundamental definition for the intensity of illumination.

In the comparison of light sources, their intensities are considered at various distances; a light source whose illuminating intensity is $P$ units, as above defined, will, at a distance of $r$ metres, show an intensity of $P'$ units, following the *law of distances ;* the relations between these three quantities are,

$$\left.\begin{aligned} P' &= \frac{P}{r^2} \\ \text{and} \qquad P &= P'r^2 \end{aligned}\right\}. \tag{28}$$

**36. The unit of intensity of a light source.** — From the equation,

$$I = \frac{Q}{S}, \tag{29}$$

the unit illuminating intensity of the light source is seen to follow from unit values for $Q$ and $S$. Then *a light source of unit illuminating intensity produces unit illumination of a square metre of concentric spherical surface at a radial distance of one metre.* The radiating strength of the source is, however, $4\pi$ units of quantity of light.

**37. The intrinsic brightness of a light source.** — Referring again to a light source as a small luminous sphere, suppose it emits $Q$ units of quantity of light from a light-producing area

of $U$ square centimetres, the intrinsic brightness $B$ of the source is,

$$B = \frac{Q}{U}. \tag{30}$$

Or, *the intrinsic brightness of a light source is defined by the quantity of light emitted for a square centimetre of its area.*

**38. The generalized photometrical law.** — The statement that the quantity of light on a given surface varies directly as the illuminating strength of the light source (equation 25), and inversely as the square of the distance from it, presupposes

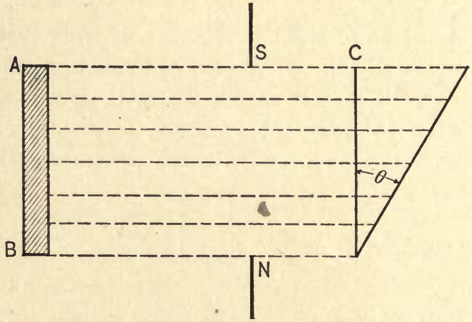


FIG. 9.

that all compared surfaces are parallel each to each. It is necessary, however, to pass from this special case to a perfectly general one, in which the normals to the surfaces compared may make an angle with each other or the light rays. In Fig. 9, $SN$ is the opening in a screen and $AB$ a section of a luminous surface, and $CD$ and $C'D$ are surfaces illuminated by $AB$. If $\theta$ is the angle which the normal to the surface $C'D$ makes with the light rays, while the surface $CD$ is normal to them, the illuminated areas of $CD$ and $C'D$, $S_1$ and $S_2$, respectively, will receive a like quantity of light upon them and are in the relation,

$$S_1 = S_2 \cos \theta. \tag{31}$$

The quantities of light upon unit surface of each are,

$$q_1 = \frac{Q}{S_1} \tag{32}$$

and
$$q_2 = \frac{Q}{S_2}. \tag{33}$$

Employing the values from equation 31,

$$q_2 = q_1 \cos \theta. \tag{34}$$

The quantity of illumination received on any given surface thus varies directly as the cosine of the angle of deviation of its normal from the paths of the light rays.

But the quantity of light falling on unit area is a measure of the intensity of illumination; so in general, the intensity of illumination $I'$ on any surface is related to the normal intensity $I$, by,

$$I' = I \cos \theta. \tag{35}$$

This important relation is commonly called *Lambert's law of the cosines*, since it was first enunciated by him.* The importance of this law arises from its application in defining the illuminating power of a light source which in practice is given in the measure of the intensity of the illumination of a surface.

Conversely, if the source of light should be the surface $C'D$, its intrinsic brightness $B'$ at $AB$ would have a value, $B$ being the intrinsic brightness normal to $C'D$.

$$B' = B \cos \theta.$$

**39. The nomenclature of photometrical quantities.** — The unit quantities which have continually recurred in this discussion

* Lambert, Photometria, 1760. Consult Jamin, Cours de Physique, III (3), page 31. Also consult "The Photometry of the Diffuse Reflexion of Light on Matt Surfaces," a critical examination of Lambert's law of the cosines; H. R. Wright, Philosophical Magazine, February, 1900, page 199.

have been defined and discussed without an attempt at their designation by special names.

The tendency toward particular nomenclature of physical quantities has been carried to a burdensome excess in many cases, until it has assumed the nature of scientific fetichism; and it materially operates against the *unity* of physical sciences and their applications.

With names assigned to the fundamental physical quantities, derived dimensions and units do not call for special designation, other than such as is *physically descriptive.* Attempts at nomenclature of the photometric quantities have been made notably by Hospitalier* and Macfarlane.†

## THE PRACTICAL UNIT OF ILLUMINATING POWER

**40. The candle-power unit.** ‡ — It has been an almost universal custom to refer the intensity of light sources to that of the candle and to designate their illuminating property in terms of the *candle power.* The name is consequently one originated from custom, and not scientific practice and usage. The term has been generally used in Germany, England, and the United States, while in France the standard of light having been chiefly the carcel lamp, the light unit has been called the *carcel.*

The origin of the candle-power unit is clearly indicated by its name. When candles were generally used for illumination there was no great variation in the size of the moulds, and the same materials were commonly employed in making them; and though there was no apparent design about the matter, yet the result was there existed comparative uniformity in the character of the materials, size of wicks, and the finished candles.

* La Lumière Électrique; 53, 1894, page 7.

† "Units of Light and Radiation," Transactions American Institute of Electrical Engineers, 1895, page 85.

‡ W. M. S., "The Candle Power of Arc and Incandescent Lamps," American Electrician, March, 1899, page 113; and June, 1899, page 261

A candle flame much exceeding two inches in height begins to smoke; consequently the wick would be snuffed before the flame attained a smoking height, and this condition, together with the close resemblance of candles wherever made, insured a greater uniformity of illuminating power from candles than has been obtained from any subsequent light source. It is thus readily understood why the candle came into use as a simple, concrete unit of light when there began scientific comparisons of illuminations and light sources.

Accordingly, to-day we speak of the measure of the light of an incandescent lamp, arc lamp, or gas flame, in terms of the candle power. Yet this adherence to the use of an obsolete term has more to commend it, than, for example, the use of the foot as a unit of length; for, though the metric system affords a unit much superior to the foot, there is as yet no photometrical unit to displace the candle in general acceptance.

The action of the American Institute of Electrical Engineers and of the National Electric Light Association in giving official indorsement to the opinion and usage of those who have fully investigated the subject, legalizing the amyl acetate lamp as the standard of illuminating power, renders all forms of candles obsolete for the light standard. Relinquishing the candle as the concrete light standard, should the term "candle power" be retained?

For illustration: suppose the metre was the generally legalized standard of length, and that this action was generally accepted and measurements were made with metre sticks instead of foot rules, would it be advisable to employ the ratio of the metre to the foot, and having made the measurements in the metre unit, to express the measured dimensions in feet?

Much the same dilemma presents itself to photometricians. Scientifically and legally, candles are no longer in repute, and the amyl acetate standard is the accepted unit of light. Shall a ratio, then, even if it were possible to obtain it, between the amyl acetate lamp and the candle be employed, and all determinations of the light strength of illuminating sources made

against the amyl acetate standard be finally expressed in candle power terms?

The numerous candle power ratings of the standard candle in the literature of photometry are only mean values obtained between wide extremes, or merely figures, and represent no physical quantity. The term "candle power," then, being meaningless as a quantitative expression, and the amyl acetate lamp being fairly precise as a standard light, photometricians might follow the example, notably of German practicians, and express illuminating power in terms of Hefner units (*Hefner Licht* is the current term in Germany).

A reasonable objection to such a procedure is, that a change once made, a better light standard than the amyl acetate lamp might be introduced and the necessity would arise for a second revision of the name of the light unit; and so on indefinitely. Referring again to the analogy between this subject and the metre as a standard of length, it may be advanced that the metre is a purely arbitrary standard of length, though it was designed to be an absolute one, and for similar reasons the candle power may be retained as an arbitrary light unit both in name and assigned value. The analogy is only apparent, for there can exist no material representation of the candle power unit of light, since it is an indeterminate quantity. Candle power is, then, a mere name corresponding to no physical quantity, and in the adoption of the Hefner unit along with the material amyl acetate standard there is in reality nothing to relinquish but a custom.

According to established scientific precedents there is no in consistency in naming the unit of light after an individual connected with its development. This custom, now seemingly well established, is at best a questionable one. The more rational procedure would be that followed with reference to heat. A quantity of heat is expressed in terms of Heat Units or British Thermal Units.

Applying this to the present discussion, the term "candle power" as well as personified terms might reasonably be aban-

doned and the illuminating power of light sources be expressed simply in *Light Units.* As the science of light standards advances and the light strength of actual standards becomes expressible with very great precision, the term "Light Unit" will apply with equal force. If the value of the light unit is changed by the action of a congress or other body, it will cause no more confusion than was occasioned by the change in the value of the heat unit by a redetermination of the mechanical equivalent of heat.

The unit for expressing the quantity of a phenomenon must be of the same character as the thing measured; and this unit value can be no more precise than the value of the thing measured. As the measurement of the phenomenon grows more and more precise, to that extent will the value of the unit become definite.

**41. The candle-power unit of illumination** is *the illumination received on a concentric spherical surface of one square metre in area at a radial distance of one metre from a source of light whose intensity is one candle power.*

Denoting the intensity of the illumination by $I$,

$$I = \frac{Q'}{S'}, \tag{36}$$

where $Q'$ is the amount of light falling on a spherical surface of $S'$ square metres; and a general expression for intensity of illumination in terms of the candle power ($C.\ P.$) of the source and at a radial distance $R$ metres is,

$$I = \frac{C.\ P.}{R^2}, \tag{37}$$

the result being expressed in terms of the candle-metre.

For the average eye, ordinary print may be easily read with an illumination of 4 to 6 candle-metre units of intensity which at a distance of two metres corresponds to a light source whose illuminating power is 16 to 24 candles.

## MEAN SPHERICAL INTENSITY

**42. The theory** of the subject will first be considered and that from a geometrical standpoint. In Figure 11, $O$ is the centre of the polar coördinates along which certain radial distances are platted, while the curve joining their extremities has a contour somewhat resembling the distribution of the luminous in-

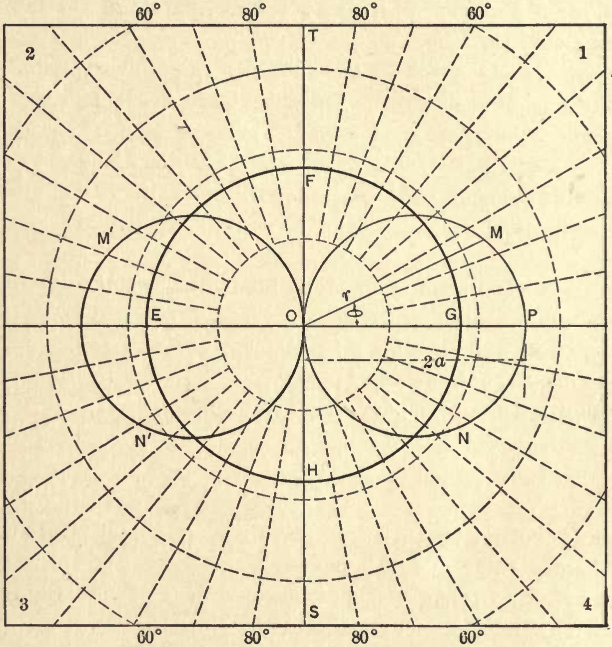


FIG. 10.

tensity about an alternating current arc. The problem is to find the mean radial distribution about the centre $O$.

Considering the case shown in Figure 10, wherein the curve is a circle $OMN$ whose periphery passes through $O$ tangent to the vertical coördinate $TOS$, the polar equation to such a curve is

$$r = 2\,a \cos\theta, \tag{38}$$

$a \equiv \frac{1}{2}OP$ being the constant radius of the curve and $r$ the variable distance along the polar coördinates from $O$ to the periphery of the circle $OMN$.

The area included by the circular curve is found by double integration of

$$A \equiv \text{area circle} = 2\int_0^{\frac{\pi}{2}}\int_0^{2a\cos\theta}(d\theta)(rdr). \tag{39}$$

It is to be observed that the law of the variation of the distance from the centre $O$ to the curve is known, and this distance is a continuous function of the inclination to the polar axis. Similarly, in all cases in which the radial distance is known to be a continuous function of the inclination the area included in the curve may be found.*

Further, it is supposed that the circle is a section through a figure of revolution about the vertical coördinate $TOS$ as an axis; and it is desired to find the dimensions of an equivalent sphere whose radius shall be the mean radius of the figure of revolution. The section of the figure of revolution taken through the axis $TOS$ would show two equal circles $OMN$ and $OM'N'$, having each the area $A$ as found by equation 39.

The section through the equivalent sphere having the centre $O$ in common with the figure of revolution will be a circle whose area is $2A$, the area of the section of the figure of revolution. The radius $r'$ of the mean sphere is then readily found, and is

$$r' = \sqrt{\frac{2A}{\pi}}. \tag{40}$$

In the figure the area of the circle $EFGH$ is taken as double the area of $OMN$ and represents a prime section through the mean sphere, and $EO$ is thus the mean spherical radius of the equivalent of the figure of revolution.

When the equation to the curve can not be stated, or rather

* Consult Murray, Integral Calculus, Chapter IX, for a discussion of the area included by a polar curve.

the radial distance is not a continuous function of the inclination, the area can not be integrated by purely mathematical processes, and recourse must be had to mechanical integration. This may be done either by a planimeter or a graphical construction.

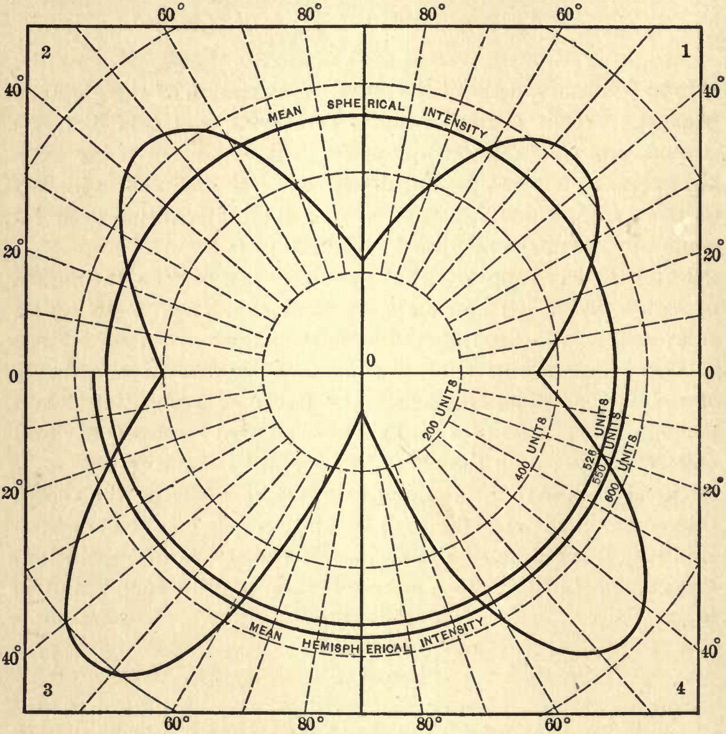


FIG. 11.

The four loops in Figure 11 are such an instance, and represent a distribution which is different in each of the four quadrants. In this figure, the area bounded by the curved contour and the rectangular axes is found for each quadrant, and the sum of these areas is equated to the prime section of the

equivalent mean sphere, the radius of which is then found by the equation:

$$r' = \sqrt{\frac{\Sigma A}{\pi}}. \tag{41}$$

## THE PRACTICE OF THE MEAN SPHERICAL INTENSITY

**43.** It is evident that the light source which has been assumed — a small equably luminous sphere — is not met with in practice. With the incandescent lamp, the light source is a looped, luminous filament, and the base of the lamp prevents the emission of light in that direction. With the arc lamp, the distribution of light varies widely with the type and in all cases shows marked irregularity. Similar conditions exist with gas flames and incandescent gas mantles. Also the distribution of the emitted light is again profoundly varied by the use of reflectors, and enclosing chambers and globes. (Appendix A.)

These irregularities of distribution render it difficult to specify the illuminating power of any of these light sources in general terms; and the comparison of one light source with another is no less difficult and ambiguous. This subject is at once both scientifically interesting and of great practical importance.

The light distribution (see Fig. 50, page 196) about an incandescent filament is a function of its cross section and the form of the loop. To express its illuminating power with accuracy, the radial direction along which it is specified must be noted, whether it is horizontal, vertical, or at a given angle of inclination to the horizontal plane through the filament; and the azimuth, too, must be given. Incandescent lamps having filaments of different shapes cannot be directly compared, for their light distribution is not similarly intense along a specified vector or radius.

The light distribution about the open arc of a continuous current lamp is notably deformed from a spherical one; nor is the distribution constant, for it varies from time to time, as

the carbon tips burn to a new shape. It also varies with the size and quality of the carbons burned. So irregular is the distribution that the statement of the illuminating power of a given arc is without significance unless it is stated along a specified vector. The problem increases in complexity and uncertainty as the arc lamp considered is of the alternating current type or is an enclosed arc. The case is similar for gas flames of different types and is here further complicated by reflectors.

The practical applications of these varied light sources as well as their scientific uses render a system imperative for the specification of illuminating power and comparison of illuminating intensity. The theory of such a system has been stated and it now remains to point out its applications.

The arc lamp being so pronounced in the peculiarities of its light distribution, will alone be considered in this discussion; for any light source whatever may be similarly investigated.

In Figure 11 is shown a distribution of luminous intensity about an alternating current arc; and while the distribution is not strictly a figure of revolution, or symmetrical about any axis, the curve shown is the distribution on a vertical plane through the arc centre, and will be considered as an average of all similar plane distributions.

The method for obtaining such curves will be subsequently discussed (see pages 216 and 236).

The maximum intensity here exceeds 800 units, and the minimum is less than 400. The areas of the curves in the four quadrants were found to be, using a planimeter,

| | | | |
|---|---|---|---|
| Quadrant 1 | . . . . . | 4.8 | square inches. |
| " 2 | . . . . . | 5.0 | " " |
| " 3 | . . . . . | 6.1 | " " |
| " 4 | . . . . . | 5.8 | " " |

yielding a total area included by the curved contour of 21.7 square inches. This area was equated to the area of a prime section of an equivalent sphere, whose radius was found to be

2.63 inches. This circle being now considered as a section of a figure of revolution, it defines the equivalent mean spherical distribution of the light; and the radius of this equivalent sphere is 2.63 inches. Referring this dimension to the scale on which the curve was platted, the mean spherical intensity is found to be 526 units.

The meaning of this quantity is obvious: If the flux of light across the actual surface about the arc *O*, of which the curve is a plane section, was uniformly distributed over an equivalent spherical surface, this surface would be one of mean value for the flux, and the radial intensity would be the mean spherical intensity desired.

In a similar manner, if the light flux indicated by the curve in any one quadrant, such as 1, 2, 3, or 4, is alone considered, the area between the contour and the axes may be taken and equated to the area of an equivalent circle, and the radius of this circle will be that from which the equivalent mean spherical intensity of this quantity of light from the arc *O* can be found. Or, any two quadrants may be considered at pleasure, and the mean spherical intensity of the quantity of light which they represent may be accordingly determined.

**44. The mean hemispherical intensity.**—A second aspect may be given to the method: Suppose that the light flux indicated by the curves in quadrants 3 and 4, Fig. 11, is considered only with reference to the light distribution below the horizontal plane through the arc *O*, the sum of the areas included between the curves and the axes of the quadrants 3 and 4 is equated to an equivalent semicircular area, and the radius is found as before. By means of this radius the mean hemispherical distribution is defined, which in the case platted amounts to 550 intensity units. This lower mean hemispherical intensity is greater than the mean spherical intensity taking the four quadrants into account, since the flux of light over the space below the horizontal plane is in excess of that above it, as is shown by the curves.

A better defined case is shown in Figure 12; the light distribution was platted only over the section below the horizontal plane through the arc *O*. The areas included are,

| | |
|---|---|
| Quadrant 3 . . . . . . | 6.55 square inches. |
| " 4 . . . . . . | 6.65 " " |

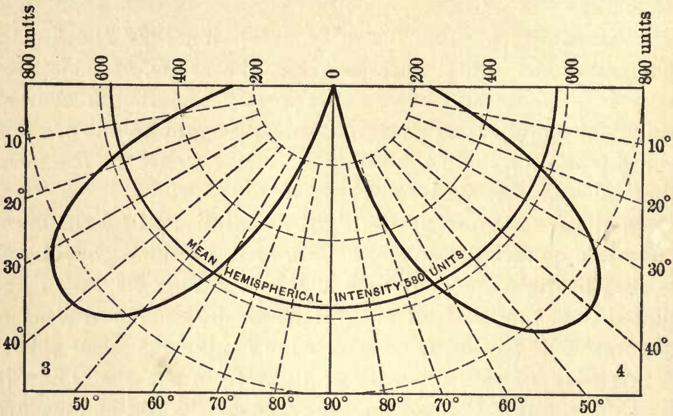


FIG. 12.

Their combined area of 13.2 square inches is equivalent to the area of a semicircle of 2.9 inches' radius, which scaled, defines the mean hemispherical intensity of 580 units.

In the general consideration of continuous current arcs, the mean hemispherical, rather than the mean spherical intensity is of value, for the illumination of such an arc is utilized in the horizontal plane and below it.

It is obvious, however, that the mean spherical and hemispherical values have but little practical bearing on questions of illumination in general. For the specific illumination of an object or for illumination in any specific direction, the actual intensity in such direction is the important quantity to be determined; but for the complete comparison of one light source with another, and for ascertaining the efficiency of any light source, the mean spherical value must be considered.

# CHAPTER III

## PHOTOMETERS

### THE ELEMENTS OF THE PHOTOMETER

**45.** ANY comparable or measurable effect of light may be taken as a basis for photometry, and an apparatus designed for utilizing it. From time to time a large number of photometers, employing various effects of light, and embodying, perhaps, only a slight modification of some previous form, have been proposed, and certain of these have proven their practical worth.

The attempt to trace the historical development of the photometer, and to describe the various forms which it has in turn assumed, belongs rather to the physical treatise on the subject, and could not be adequately discussed within prescribed limits, and would appeal to the investigator rather than the practician.

The present tendencies in photometry are toward a development of the light standard, and of standard conditions of illumination; for the sensitiveness and adaptability of available apparatus for the comparison of lights are now greatly in excess of the reliability of the standard of light.

The present discussion will be confined especially to certain photometers which have a demonstrated practical value, and to certain principles of design which are favourable for further modifications; and to a brief historical outline of the development of the photometer into approved forms. The gas lighting industry has been the occasion for the proposal and introduction of a very large number of types of the photometer,

and those which have not proven useful in the photometry of electric lights will be omitted, as they do not properly find a place in this work.

**46. The photometer defined.** — The term "photometer" will be used in this discussion with a restricted meaning. As ordinarily employed the word applies to the entire apparatus, simple or complicated, which is especially designed for measuring the relative intensities of luminous sources, and thus includes the bench or mounting, the observing screen, and, possibly, the standard of light and other accessories. In a broad sense no exception can be taken to this; but in a work devoted to the measurement of illuminating sources it becomes necessary to discriminate and insist upon rather narrow classifications, which, sharing the character of restricted classification in general, may often become arbitrary.

The act of measurement involved in photometry is confined to observations of the illumination of the lights compared upon some form of screen; and taking this as a basis, *the photometer is the screen and its accessories.*

In the photometrical train of apparatus the standard of light is the fundamental feature, and its importance is so great that it demands a very considerable discussion. A working standard being available, the next essential feature is the photometer or a suitable observing and comparing apparatus.

**47. The photometer** consists in all its modifications of a screen, which is a device for receiving the illumination from the light sources compared; it may have in addition a containing case, or mounting, with an ocular aperture or an observing telescope; and the whole may be fitted to some form of carriage, or ways, if movable, for setting it at certain points along a bar or guide, which forms a part of what will be called the bench.

**48. The photometer bench,** as its name indicates, is a device for mounting the lights compared and the photometer, and is fitted with appropriate scales. The bench proper may consist

of bars or rails, which form a track for the two carriages mounting the lights under comparison and the photometer carriage; or it may be a simple base fitted with guides, and in any case some form of scale is attached or marked on it for indicating the respective distances between the screen and the lights. In some forms the photometer is stationary, while the lights are movable along ways. In a few apparatuses of compact form, the bench becomes a containing case for the other members.

**49. The screen.** — In their operation screens either reflect or diffuse the illuminations under comparison. They may be observed directly by the unaided eye or through the agency of some optical train.

**50. The reflecting screen** acts by irregular and not specular reflection. The specular reflection from the plane surface of a mirror or its equivalent would produce an image of the source of the light in the eye with diminished brightness, and no effect from which the illumination caused by the light could be observed.

In photometry the illumination caused by a light is the quantity directly investigated, and the brightness of the light producing it is derived by inference.

The surface of the reflecting screen, then, must be finely and uniformly grained in order to scatter the light regularly incident upon it; yet the grain must not be so marked that it will be distinctly visible. Such a surface reflects the light irregularly, and the light effect on the eye is that of illumination, filling the eye with light and not with an image of the light source (page 8).

The light reflected from the screen will always be diminished in amount, and may or may not be materially changed in quality. The sensitiveness increases in proportion as the loss of light by reflection is diminished.

The principle of selective absorption is occasionally utilized in screens, when by the use of an appropriately coloured surface

the light is modified in its reflection to agree in colour with the compared light.

Paper is a frequently used material for the screen, while excellent ones are made from finely grained plaster of Paris or from magnesium oxide or carbonate, and similar substances. All screens of this class diffuse the incident light by reflection.

**51. Diffusing screens** are distinguished from the preceding class by their property of scattering the light in its transmission through them. They are made from some translucent substance, and of sufficient thickness to prevent the image of the light source from being formed in the eye. In their operation these screens always reduce the intensity of the light, and they may be designed to change materially its quality by selective absorption.

The sensitiveness of diffusing screens is dependent upon the extent to which they are translucent. Their translucence may be due to one of several causes. The screen may consist of a transparent matrix, such as a layer of gelatine, or celluloid, having uniformly mixed through it some finely divided solid. The light in passing through such a film is reflected from the surface of one small particle to another, issuing after a large number of such reflections in a diffused state. A large part of the light is necessarily absorbed in the process, it being diminished to a certain extent by each reflection in the series. Screens of this character are not highly sensitive and are apt to change the quality of the light in its passage through them. Opal glass is a variety against which this objection is especially urged.

A second method for making a translucent screen depends upon the multiple reflection of the light from a great number of small surfaces, by the method of total reflection at the bounding layers between two media of different densities. The translucence of the foam from a transparent liquid is caused in this manner.

**52. Materials for translucent screens.** — This character of screen possesses such excellence that it has been successfully employed in a number of important investigations, especially by Violle.* It should be carefully considered by the photometrician, as it is capable of many useful applications.

Serviceable screens of the tissue variety may be made from thin paper of fine texture, preferably such as is not calendered and filled with earthy materials. Their sensitiveness may be increased by treatment with any preparation which will render them more translucent without causing them to become transparent. Very thin tracing cloth being of a similar nature may also be used to advantage. Formerly very thin shavings of horn were considered to make good screens. The sensibility of this variety of screens is low, and they are not adapted for work requiring great refinement in the observations, though they may prove satisfactory in ordinary practice.

Opal glass, though seemingly a suitable material for a screen, should be avoided. Its opalescence is caused by very finely divided solids suspended in the sheet of clear glass. Owing to the fineness of these particles, they perceptibly change the quality of light passing through the glass until it assumes a reddish yellow tinge. The particles are sufficiently large to reflect back and dissipate the violet rays, but are too small to affect the slower rays toward the red end of the spectrum to any considerable extent.† These strictures apply equally to opalescent celluloid films or other films containing suspended solid matter.

Transparent sheets having a matt surface imparted by grinding or etching are not to be confused with the opalescent screens. They owe their translucence to a surface broken up into very minute grains or elevations having bright surfaces, which are good reflectors and diffuse the light without change in quality and with comparatively little loss. An objection is urged against these screens, that they soil readily, and the sur-

*La Lumière Électrique; 34, page 52.

† See Tyndall, Heat as a Mode of Motion, page 483.

face once injured by dirt or grease can not be restored. However, with proper treatment the diffusing power of the surface can be almost wholly restored. Films of matt celluloid, while not so durable as ground glass, yet give good service and are fairly sensitive.

The most sensitive screens are those in which transparent substances of different densities are combined. Foucault* used a thin layer of milk dried on plate glass. Thin starch water dried on glass, too, answers a good purpose. Crova obtained the best screens by using beet-root starch, which is characterized by very small spherical granules of great transparency.

**53. The sensitiveness of a screen** depends directly upon its luminous efficiency determined by the ratio of the light delivered, to the incident light.

The sensitiveness of the photometer setting is ultimately determined by the magnitude of the least light change which is visible to the observer, which may vary from $\frac{1}{60}$ of the total illumination when this is weak, to $\frac{1}{120}$ or even less when it is bright.† Whatever this least change may be for the particular observer and observation, the vision can not be rendered more acute by any amplifying instrumental means.

The criterion for the sensitiveness of the screen demands that it shall deliver to the eye a sufficiently brilliant illumination to enable the eye to distinguish the normal visual difference, say the $\frac{1}{100}$ part. That the screen may accomplish this associated with very great sensitiveness in the setting, it is essential that the compared lights be separated to a considerable distance. For a screen of low optical efficiency to satisfy the criterion for sensitiveness it is necessary to place the compared lights close together, a proceeding which reduces the sensitiveness of the settings, with a resulting wide limit of uncertainty in the pho-

* Crova, Annales de Chimie et de Physique, Ser. 6, VI, page 342; an excellent description of such screens.

† Helmholtz, Physiolog. Optik, page 328.

tometrical values measured. To remedy this latter fault, screens of greater optical efficiency must be used that the lights may be worked at a greater separation. Whatever design the screen may assume, it is theoretically satisfactory with a given separation of the lights so long as it transmits a sufficiently brilliant illumination for acute vision, and one screen is superior to another within such limit only so far as it has some provision for sharply defining the boundaries of the illuminated fields compared.

**54. The Inclination of the Screen.** — Generally screens are so placed that the light falls upon them along the normal to their surface. But the illumination of the screen may be varied, providing the surface is regular, by inclining it to the photometrical axis, instead of changing the distance from the light source (page 32). If $Q$ is the total light falling upon the screen, and $a$ its coefficient of reflection, and $\theta$ the angle of inclination of its normal to the photometrical axis, the reflected light $Q'$ will be

$$Q' = aQ \cos \theta. \tag{42}$$

An application is made of this in a few photometers, and to some extent in arc-light photometry. When the screen has an uneven surface, such as rough-grained drawing paper, this law is not closely followed.

**55. A classification of screens.** — This part of the apparatus is variously modified in different types of photometers, and in some cases is combined with more or less complex optical devices for the purpose of comparing the diffused illuminations from the light sources. Regarding their action, screens may be divided into two general classes.

*The Simple Screen* is characterized by a surface from which the light from the luminous sources under comparison may be reflected in a diffused state that it may be viewed by the eye as an illumination; or is a film, sheet, or plate, which similarly diffuses the light from the sources in its passage through it.

*The Compound Screen* is one whose action depends upon diffuse reflection from the surface, combined with transmission through a translucent portion. Such a screen, for instance, characterizes the Bunsen photometer.

## THE BOUGUER PHOTOMETER*

**56**. This, said to be the oldest form of apparatus devised for comparing the intensities of luminous sources, was constructed by Bouguer prior to 1760.† It is naturally the first

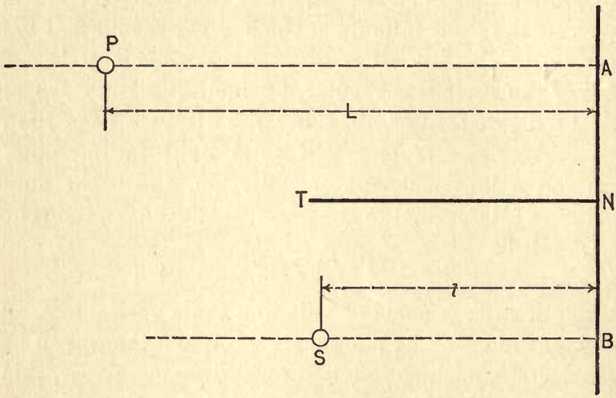


Fig. 13.

device that would suggest itself to one seeking to apply Kepler's law of the inverse squares.

The compared lights *S* and *P* (Fig. 13) are placed in front of an opaque reflecting screen, *AB*, so that they illuminate it normally to its surface. A blackened partition *TN* divides the

* Essai d'Optique, 1729; also Traité d'Optique sur la gradation de la lumière; Paris, 1760.

† Bouguer died in 1758, though his work announcing the photometer was not published until 1760. The date of the publication of this work on optics has been confused by some with that of the construction of the apparatus.

screen into two equal portions and extends outward normally from the screen to such a distance that none of the light from one source shall fall on the opposite half of the screen. The lights were moved perpendicularly to the screen to obtain an equality of the illuminations. The distances of the lights $S$ and $P$ from the screen being respectively $l$ and $L$, the law of inverse squares gave

$$P = \frac{L^2}{l^2} S. \tag{43}$$

Later, Potter,* to protect the observer from the lights themselves, substituted a translucent screen of matt glass, or paper, to enable the observer to place the screen between himself and the lights.

As will be seen, many of the later photometers were merely modifications and refinements of one or the other of these primitive forms.

## THE RUMFORD, OR SHADOW PHOTOMETER

**57.** This apparatus is similar to that designed by Bouguer, but an optical device replaces the partition. The method seems to have been first devised by Lambert, who, in 1760, published a very elaborate study of illumination and its comparison.† Subsequently the shadow principle was employed by Benjamin Thompson (Count Rumford) in such a way as virtually to rediscover its use to scientists, and from this fact it received the name of the Rumford Photometer.‡

Rumford placed a white screen against the wall and held a small cylinder of wood in front of it, about two or three inches in length and one-quarter of an inch in diameter. The lights were then moved about until an equality of the shadows was

* Edinburgh Journal of Science, New Series, III, page 284.

† Photometria sive de mensura et gradibus luminis colorum et umbræ, 1760.

‡ Philosophical Transactions, 1794, Part I, page 67; a letter to Sir Joseph Banks from Benjamin Thompson on shadows, etc.

found, when their relative intensities were calculated by the law of inverse squares.

In the usual form of the apparatus the cylinder was permanently mounted in front of the screen. The post $O$ (Fig. 14) prevents the light from $S$ from falling upon the screen $AB$ at $s$, and similarly the light from $P$ at $p$. The shadow $s$ from $S$ will be illuminated by $P$, and in turn at $p$ by $S$. These two

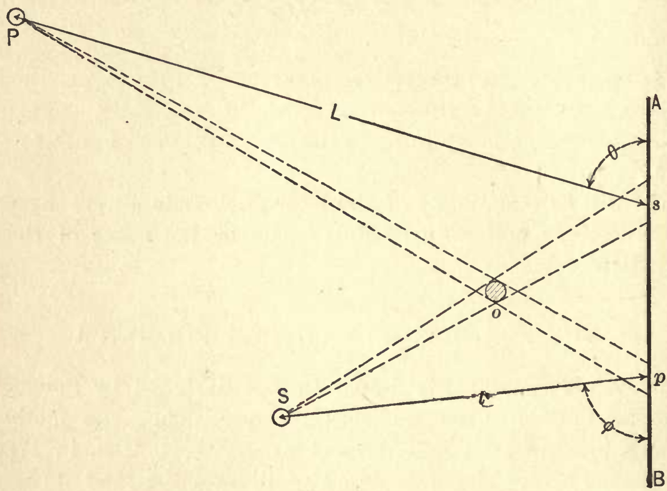


FIG. 14.

separated areas are thus illuminated by the lights $P$ and $S$ severally, and when they are brought to an equality of illumination,

$$P = \frac{L^2}{l^2} S, \tag{43 bis}$$

the distances $L$ and $l$ being taken from the lights to their respective illuminations.

The two light vectors $Ps$ and $Sp$ must have the same angle of incidence on the screen $AB$, otherwise by the generalized photometrical law,

$$P = \frac{L^2}{l^2} \frac{\cos \theta}{\cos \phi}, \tag{44}$$

$\theta$ being the angle made between $Ps$ and $AB$; and $\phi$, between $Sp$ and $AB$.

It is difficult to adjust this instrument to follow the requirement of equality of angles of incidence, for if $S$ is fixed in position, $P$ must be moved along a curved path from $O$ as the origin. The lack of sensitiveness resulting from the widely separated areas compared does not justify such an exact correction.

The screen $AB$ may be translucent and viewed from the side opposite to the lights.

## THE RITCHIE PHOTOMETER*

**58.** A radical change in photometry was made by Ritchie leading to greater compactness of apparatus and introducing the possibility of greater sensitiveness in the results.

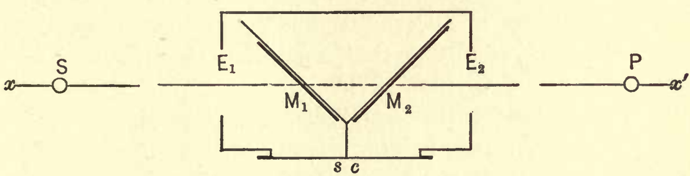


FIG. 15.

Ritchie placed the lights, as is now commonly done, in fixed positions at the end of a bar, viewing the illuminations of the screen at right angles to the common line of the lights, and moving the screen instead of the lights to obtain an equality of the illuminations. He was thus enabled to enclose his photometer in a compact sight box.

The essential feature of his sight box † were two mirrors, $M_1$ and $M_2$, Fig. 15, placed vertically and dihedrally in the box, and at an angle of 45° with the photometrical axis. That the reflect-

* For a recent modification of this screen, see an account of the Nichols-Ritchie Screen, Physical Review, 1893, page 339.

† Brewster's Journal of Science; 5, 1826, page 139.

ing power of the mirrors might be more nearly equal they were cut from the same sheet of glass. An opening in front of the apex of the mirrors was covered with a translucent screen *s.c.* such as tissue paper, and there was a blackened partition extending from the edge of the dihedral angle to the screen. The box was reversed at each setting to eliminate inequalities. The Ritchie photometer is an excellent one, and can be given great sensitiveness by substituting prisms for the mirrors and employing a proper diffusing screen.

He also discovered the properties of the inclined surface screen and used this form in his investigations.

## THE FOUCAULT PHOTOMETER*

**59.** This is a refinement of the form already described and attributed to Bouguer. J. Herschel † showed that the wide separation of the illuminated areas of the Lambert photometer was a source of uncertainty and loss of sensitiveness, and established the condition that maximum sensitiveness in the comparison of two illuminated surfaces required them to be placed immediately side by side, with edges sharply defined and divided by a very narrow separating line. This condition is fairly well met in the Foucault photometer by removing the partition a short distance from the screen and making its position adjustable by means of a screw, so that during the observation it may be moved until its shadow is reduced to a narrow band. This line of separation, however, is not perfectly dark and distinct, for it is partially lighted by irradiation from both light sources, which also causes the edges of the illuminated areas to lose their sharpness.

In order to reduce this disturbance a double screen was used with its sides inclined from the observer, forming an obtuse angle, the dividing shadow being received at its apex (Fig. 16). The two lights $P$ and $S$ were ranged respectively along

* Œuvres Complètes, page 100.

† On Light, page 29.

the normal to each surface $A_1$ and $A_2$, and both the adjustment of their positions and the calculation of their relative intensities follow methods already described. The Lambert translucent screen was used in this apparatus, and this, together with the

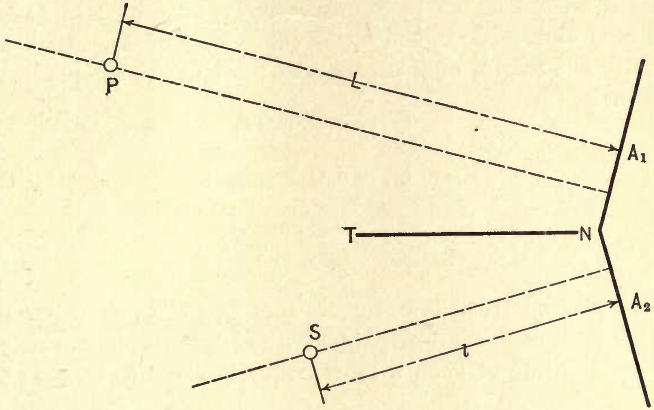


FIG. 16.

movable partition, were mounted in a containing sight box fitted with a hood to protect the eyes from the compared lights.

## THE WEDGE-SHAPED SCREEN

**60.** After placing the reflecting mirrors in a sight box, movable along the axis of the compared lights, Ritchie* proceeded to simplify the photometer, and combined the diffusion and reflection of the light on one surface by substituting sheets of paper for the reflecting mirrors.

He mounted pieces of cardboard, cut from the same sheet, and placed with like surfaces outward in the place of the mirrors, Figure 15. A wedge-shaped screen was the result, which was viewed from the opening in the sight box from which the tissue paper screen and the partition used with the reflecting mirrors were removed.

* Ritchie, reference cited.

**61. On the theory of the wedge-shaped screen.** — The sides of the wedge screen must be symmetrically placed in the photometrical axis, that the light may be incident at the same angle upon each surface. For if $Q_1$ and $Q_2$ be the normal illuminations on the screen faces respectively, and $Q'_1$ and $Q'_2$ the reflected light, and $a_1$ and $a_2$ the coefficients of reflection, and $\theta$ and $\phi$ the angles of inclination of the sides to the photometrical axis, then

$$Q'_1 = a_1 Q_1 \cos \theta, \tag{45}$$

and

$$Q'_2 = a_2 Q_2 \cos \phi, \tag{46}$$

or

$$\frac{Q_1}{Q_2} = \frac{a_2 Q'_1 \cos \phi}{a_1 Q'_2 \cos \theta}. \tag{47}$$

The photometrical law requires that $Q_1$ and $Q_2$ shall be equal for the condition of the photometrical balance, and certainty in the working of such a screen equally requires that $Q'_1$ and $Q'_2$ shall be equal.

These requirements are met by placing the sides of the screen at the same angle toward the photometrical axis and using surfaces of like reflecting power on each side of the wedge. The most efficient reflecting angle will be discussed in a subsequent paragraph.

**62. The Conroy photometer.** — Within recent years the wedge screen has again received attention. Experimenting with a Ritchie wedge, Conroy* experienced much difficulty with the apex of the wedge. If the paper was bent around this, there was no well-marked line of separation between the two sides; nor by cutting the paper and matching the edges was the separation as sharp as he desired. For maximum sensitiveness the two illuminated fields should meet in a common dividing line, which should be entirely distinct and very narrow.

He secured high sensitiveness by modifying the Ritchie wedge. In the sight box shown in plan in Figure 17, $A_1$ and

* Philosophical Magazine; 15, 1883, page 423.

$A_2$ are two wooden prisms fastened to the base, placed so that the sides $B_1$ and $B_2$ make an angle of 60° with the photometrical axis $xx'$. Similar pieces of white paper or cardboard were attached to them, and the piece mounted at $B_2$ had the edge toward the second prism trimmed sharp and straight.

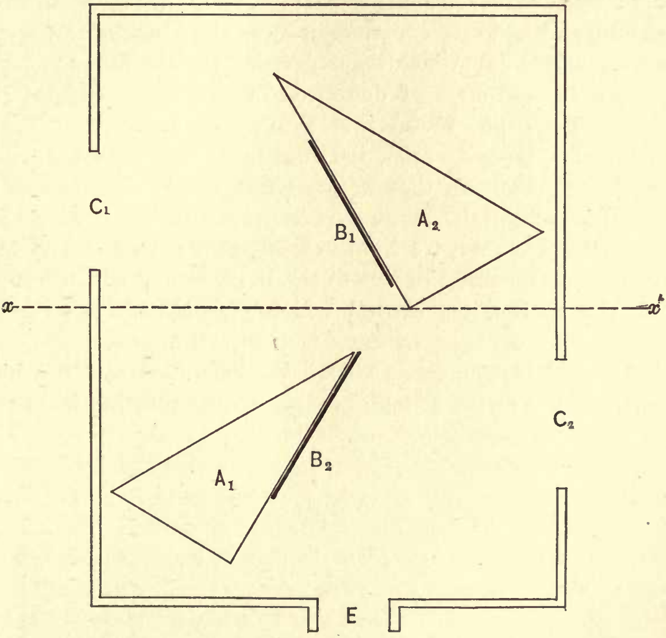


FIG. 17.

The halves of the screen were illuminated through the openings $C_1$ and $C_2$ respectively, and the prisms were staggered on the base so that the eye placed at the opening $E$ would see the side $B_2$ projected on $B_1$. This form has the disadvantage that one half the screen is nearer the eye than the other.

Conroy also studied the best angle of reflection. He found that when light was incident on the paper surface at an angle

of 45°, considerable glare or specular reflection occurred. This was completely obviated by reducing the incident angle to 30°; which would indicate that for the simple reflecting wedge of Ritchie, the dihedral angle should be 60°.

**63. The Thompson photometer.** — The Ritchie wedge-shaped screen was revived some years since, and, though practically unmodified, was known commercially as the Thompson-Starling screen. These experimenters experienced a like difficulty with the lack of sharpness of definition of the apical edge of the screen. They also found that a dihedral angle of 90° gave considerable specular reflection that interfered with the working of the screen, so they finally adopted a working angle of 70°. The material of the screen was cardboard, and they endeavoured to compare lights of different colours by using a surface corresponding in tint to the light, a plan which fails to yield the desired result, and which may introduce an error through the unlikeness of the screen surfaces.

Subsequently Thompson* devised a modified screen, which is really an inverted Ritchie wedge. The reflecting faces of a

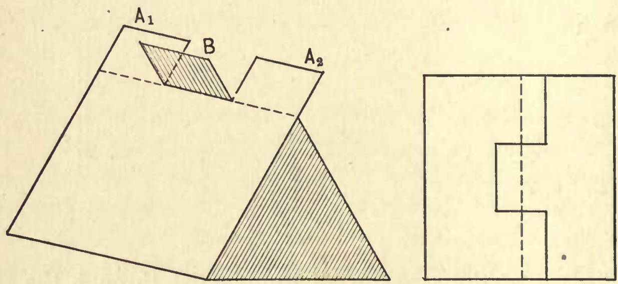


FIG. 18.

wooden prism were covered with cardboard, as in other cases; but this was so cut at the edges that tongues projected at each side, as is shown in Figure 18 in plan and elevation. The

*S. P. Thompson, Philosophical Magazine; 36, 1893, page 120.

tongue $B$ is illuminated by one light source, and the tongues $A_1$ and $A_2$ by the other. The impression on the eye made by the illumination of the tongue is supported by the similar illumination of the card surface from which the tongue projects. At the same time, after the manner of the Conroy screen, of which this is a development, the illumination of one field is projected on that of the other.

This form of screen has much to commend it. The remaining details of the photometer were similar to those used by Ritchie.

## THE PARAFFINE DIFFUSION SCREEN

**64.** This form of screen suggested by Elster * may consist of a two-inch cube of homogeneous paraffine which is divided centrally, and a thin sheet of metal or other substance impervious to light and not attacked by the impurities in the paraffine is inserted between the halves and the whole then pressed firmly together. The cube is placed in the usual form of sight box and centred in the photometrical axis, with the dividing plane at right angles to it.

The light falling normally on the faces of the cube is spherically diffused, and each half of the cube being illuminated from its respective light source, will present two illuminated fields from the face toward the observer. The fields will be sharply defined from each other by the thin partition, and an easily read and fairly sensitive screen is the result. The diminution of the light is the marked disadvantage of this form of screen. Instead of paraffine, any translucent solid, such as stearine, may be employed.

A permanent screen may be made from plates of opal glass, but this material is objectionable in that it alters the quality of the light by differential or selective reflection.

This type of screen may be given almost any degree of sensitiveness that an investigator may desire, by constructing an optical cube with plate glass faces and placing in it a thin

* Carl Reportorium, IV, 1868, page 171.

metal partition, which, however, should not extend entirely to the back of the cube.

This vessel is filled with distilled water, and a few drops of stannous chloride are added, and the liquid stirred until it is uniformly diffused. By decomposition, basic stannous chloride is formed, and imparts a milkiness to the liquid. The precipitate is very finely divided, and if dense may act in the same injurious manner on the quality of the light as opal glass.

## THE BUNSEN PHOTOMETER

**65.** This is one of the oldest forms, dating from 1841, and still remains the most widely used and generally efficient means for comparing the intensity of luminous sources.

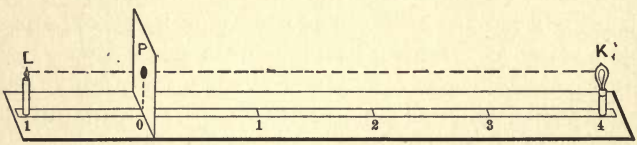


FIG. 19.

Its marked simplicity admirably adapts it for use both in the laboratory and in general practice. The type is shown in Figure 19.

In its simplest form, a sheet of white paper whose centre has been rendered transparent with paraffine, stearine, or other suitable material, is stretched on a frame. The transparent portion is given the shape of a circle or other geometrical figure, and it is essential that the edges of the design should be sharply defined. The screen is usually mounted in a sight box which is movable in the photometer axis, the arrangement being that of the Ritchie photometer.

**66. The action of the Bunsen screen.**—The screen is so placed on the photometer bench that the axis will pass through the centre of the transparent spot. The light falling on either

side is in part reflected from the white paper surface as in the case of similar screens; and a portion passes through the transparent spot, while a small amount of light is lost by absorption in each portion of the screen.

The coefficient of reflection of the untreated portion of the paper is much greater than that of the transparent portion; then so far as the action of the light facing the side of the screen under observation is concerned, it will be reflected more strongly from one portion than the other, and the transparent spot will appear somewhat dark on a white background. Assuming the light on the opposite side to be of the same tint, a certain amount will be diffused in the transparent portion and be transmitted through it. Neglecting the absorption in the screen itself, when an equal quantity of light is transmitted in each direction, the illumination of the spot should appear equally bright with that on the remainder of the screen, and the spot may no longer be distinctly visible. Then, were both sides of the screen identical, and there was no marked absorption of light in the transparent spot, this would be no more visible on one side than the other; and with some suitable optical arrangement for viewing both sides simultaneously they should appear equally illuminated.

The distance from the paper to the respective light sources may then be taken and the relative intensity of the compared source calculated in the usual manner.

**67. The mirrors.**—In order to present the two sides of the screen simultaneously to the eye, two small mirrors, $m$ and $m'$, Figure 20, are used. These are placed vertically and form a dihedral angle with each other of 120° to 140°, the precise angle being determined by the arrangement of the sight box. Practically the mirrors may be adjusted without direct reference to the magnitude of the dihedral angle, though it is essential that each mirror make the same angle with the surface of the paper.

This arrangement is frequently called the Rüdorff mirrors;

but this is an error in nomenclature, since it is not known who first suggested it.*

It is essential that the mirrors be as nearly alike in reflecting power as possible, or the unequally illuminated fields will cause confusion, unless the attention is wholly given to the comparison of the illumination of the spot with the balance of

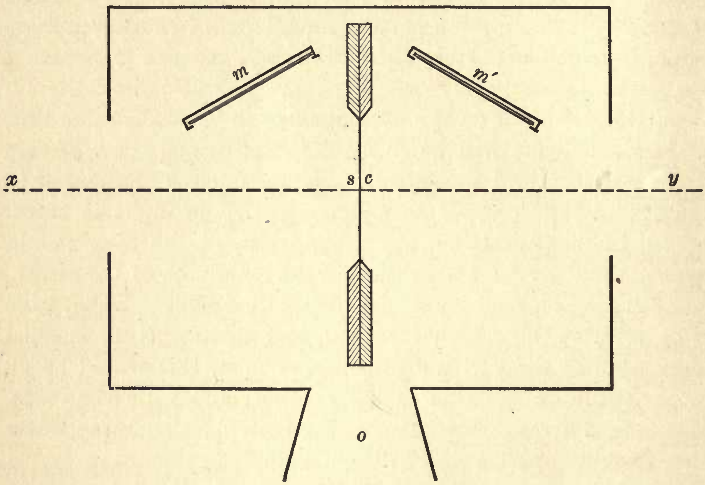


FIG. 20.

the screen. Though by means of mirrors both fields are simultaneously presented to the eye, they appear separated by a considerable distance, a condition which has been shown to reduce the sensitiveness of the setting. Yet, from one standpoint, this condition may be made an unessential in the use of the Bunsen screen. If advantage is to be taken of the compound character of the screen, then the comparison is between

* Rüdorff himself speaks of using the *known* method of two mirrors about 120° apart; Schilling's Journal, 1869, page 283. Bohn states that "mirror photometers have long been in use without it being known who originated the device." Annalen der Chemie und Pharmacie, 1859, Vol. III, page 335.

the illuminated surfaces of the transparent spot and the circumjacent area, and with a screen of like surface on each side, no comparison need be instituted between the two fields except in the special case to be discussed later.

Should, however, a comparison be desired between the intensity of illumination of each side, the two fields must be presented to the eye, lying in contact, and separated by a very narrow line. Optical devices for accomplishing this have been designed both by Von Hefner-Alteneck and Krüss.* (See page 71.)

**68. The preparation of the Bunsen screen.** — The occasion frequently arises with the photometrician to prepare such screens, for they soil readily and deteriorate after a time. It is somewhat difficult to select a suitable quality of paper. For the ordinary type of screen the paper should be of fine yet firm texture; it should be of medium thickness, without being especially translucent; and the surface should be smooth, though neither glazed nor highly calendered. A medium weight, white, and smooth linen bond or ledger paper will make very good screens.

*The transparent spot*, as has been suggested, must be perfectly sharp in outline for satisfactory sensitiveness in the setting. A greased spot will obviously not meet these requirements. Paraffine and stearine are suitable materials for making the transparent spot, and the material should be heated and printed upon the paper.

A method successfully used by the author † consists in cutting a design, such as a star or a circle, about one inch in diameter, from sheet brass; this is then fastened to a handle (Fig. 21). The plate is heated until paraffine or stearine placed upon it melts and runs freely. The excess is allowed to drain off, and when the material is on the point of solidifying, the design is firmly pressed on the sheet of paper.

* Schilling's Journal, 1884, page 587.

† W. M. S., Electrical Industries, January, 1896, page 7.

A piece of clean white blotting paper is then laid over the screen and pressed with a hot iron, in order to drive the print into the texture of the paper. If due care is exercised in the details, very sharply outlined prints can be made.

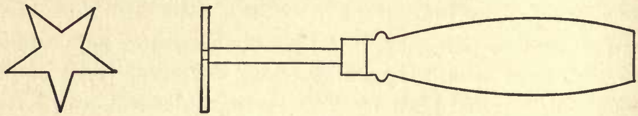

FIG. 21.

**69. The theory of the Bunsen screen.** — Though the screen itself is exceedingly simple in construction, the theoretical considerations involved in its action are by no means so; yet the elements of its theory are essential to the merest practician in order to avoid its erroneous use.

The light incident upon each side of the screen is partially reflected, transmitted, and absorbed by it. Recalling that the untreated portion of the paper is also translucent, its action is seen to be similar to that of the transparent spot, though the components in its action differ in degree from the others.

The symbols with their definitions, which will be employed, are:

$r$, the coefficient of reflection.
$t$, the coefficient of transmission.
$a$, the coefficient of absorption in the screen.
$L$, the intensity of the incident illumination.
$S$, the intensity of illumination emitted by the screen.
$d$, the distance between the screen and the light source.
$(_1)$ etc., parts on the left of the screen.
$(_2)$ etc., parts on the right of the screen.
$(')$ refers to the transparent spot.

Quantities *unaccented* refer to the untreated portion of the screen.

The general formulas for a screen, reflecting, transmitting, and absorbing the incident light, are:

$$\left.\begin{array}{l}(r+t+a)\,L=L,\\ r+t+a\qquad=1,\end{array}\right\} \tag{48}$$

an axiomatic statement first proposed by Lambert.*

The luminous intensity of the screen $S$ will be less than the intensity of the incident light $L$ by an amount due to absorption within the screen, thus:

$$S=(r+t)\,L=L\,(1-a). \tag{49}$$

For the present, then, only reflected and transmitted light will be discussed. Proceeding from the general statement of equation 49, the visual action of the screen may be expressed by four equations:

Untreated paper, left side,

$$S_1=L_1r_1+L_2t. \tag{50}$$

Transparent spot, left side,

$$S_1'=L_1r_1'+L_2t'. \tag{51}$$

Untreated paper, right side,

$$S_2=L_2r_2+L_1t. \tag{52}$$

Transparent spot, right side,

$$S_2'=L_2r_2'+L_1t'. \tag{53}$$

And $L$ may be specified from the general expression,

$$L=k\frac{I}{d_2}, \tag{54}$$

where $k$ is a constant connecting the luminous intensity $I$ of the light source with the amount of light from it falling on unit surface at unit distance in terms of the unit taken for $d$, (page 31).

* J. H. Lambert, Photometria, 1760.

From the four equations (50–53) certain conditions may be deduced. The first adjustments suggested are:

(1) That which will make $S_1 = S_1'$, when the spot should practically disappear on the left and the entire surface of the screen appear to be equally illuminated.

(2) That which will make $S_2 = S_2'$, when the spot should similarly disappear on the right side.

In practice it will be found that $S_1 = S_1'$ and $S_2 = S_2'$ are each smaller than a true mean value $S''$, which would represent the intensity of the illumination were $S_1 = S_2$, and but one setting of the screen needed; the amount of the decrement depends entirely on the nature of the screen. This suggests a third possible adjustment.

(3) That which will make $\frac{S_1}{S_1'} = \frac{S_2}{S_2'}$, or there will be an equal contrast between the untreated screen and the spot on each side, and the screen will then be at a true mean setting.

**70. The practice with the screen** may follow one of three cases:

I. Either side of the screen may be used singly, neglecting the other. One setting is made facing the left and a balance obtained with $S_1 = S_1'$; the screen is then reversed and a similar setting yields $S_2 = S_2'$. The mean of the two settings is taken for calculating the intensity of the compared lights.

This method is advised only in case the light sources are of similar tint, and the spot can be made to disappear. The mean value for the setting is slightly in error when the screen is placed at a considerable distance from the centre of the bar, though the error may be considered as negligible in ordinary practice.

II. Four settings may be made, using both sides of the screen. The adjustment $S_1 = S_1'$ is made to the left and $S_2 = S_2'$ to the right. To obviate an error due to the inequality of the sides, the screen and mirrors as well are reversed and two similar settings are made. The mean of the four settings

is then taken. The restrictions regarding the colour of the lights apply equally in this method. It offers no advantages over the first method, and requires four instead of two settings.

III. The screen is adjusted for equal contrasts on each side with $\frac{S_1}{S_1'} = \frac{S_2}{S_2'}$; and the screen and mirrors being reversed, a similar setting is made, and the mean of the two taken. This method is recommended for general practice, as it will enable lights which differ in colour to be compared.

**71. The sensitiveness of the Bunsen screen** may be examined in a general way. If a screen of this character should be so placed that $L_1 = L_2$, then from equation 49

$$L_1 (1 - a) = L_1 (1 - a'), \tag{55}$$

a relation which would hold true only in one case, that the lights suffered equal absorption in their passage through each portion of the screen. When the screen is made from a single sheet of paper, then $a > a'$; and it follows, even should both sides of the screen be identical, that at no one setting will the condition be simultaneously obeyed, $S_1 \equiv S_1' = S_2 \equiv S_2'$. Greater sensitiveness follows increased transparency in the spot, providing it still diffuses the light sufficiently; but at the same time, $a'$ also decreases.

The ideally sensitive screen would be one having zero values for $a$, $a'$, and $t$; while the value of $t'$ approached unity, and that of $r'$, zero.

The increase of the transparency of the spot must be governed by the requirements for complete diffusion of the light transmitted; otherwise, the illumination from the spot can not be properly compared with that from the remainder of the screen.

Various modifications of the Bunsen screen are possible. An opaque instead of a transparent spot may be formed on a sheet of translucent paper; or a thin sheet of opaque material may be inserted between two sheets of paper to prevent the passage

of light from one side to the other through the untreated portion, an opening being made in it for the transparent spot. The more nearly alike the surface and texture of both parts of the screen are made, the more readily the transparent spot will disappear.

The sensitiveness of any modification of the Bunsen screen may be studied from the equations given above.*

### THE LUMMER-BRODHUN PHOTOMETER

**72.** This optical train is otherwise known as the *Reichsanstalt* photometer, having been developed in connection with photometrical investigations carried out under its auspices.† Its essential feature is also named an *optical screen*, a term manifestly incorrect to distinguish this photometrical device from other screens with their accessories. This name originated in the announcement of the designers of their "substitution of a purely optical combination for the photometrical grease spot." ‡

A diffusing screen, *ik* (Fig. 24), whose coefficient of absorption is as low as possible, is centred normally to the photometrical axis, following in a sense the Ritchie arrangement. The characteristic feature of this photometer is the optical device for simultaneously viewing both sides of the screen,

* The theory of the Bunsen screen was early developed by Bohn, Annalen der Chemie und Pharmacie, 1859, page 335; and later by Rüdorff, Schilling's Journal, 1869, page 285. Probably the best discussion is given by Leonhard Weber, Annalen der Physik und Chemie, 31, 1887, page 676. Discussions by Liebenthal may be found in Schilling's Journal, 1889, pages 76 and 116; and in the Elektrotech. Zeitschrift, 1888, page 102.

† It appears that the Lummer-Brodhun optical screen was anticipated by Professor William Swan of the University of St. Andrews. His apparatus is described in the Transactions of the Royal Society of Edinburgh, Vol. 16, 1849, and Vol. 22, 1859; also consult Philosophical Magazine, January, 1900, page 118.

‡ O. Lummer and E. Brodhun, Zeitschrift für Instrumentenkunde, 1889, pages 23 and 41.

presenting to the eye light reflected from them as adjacent fields of vision. Krüss had accomplished this in 1884* in a manner closely analogous to that under discussion (see Fig. 22).

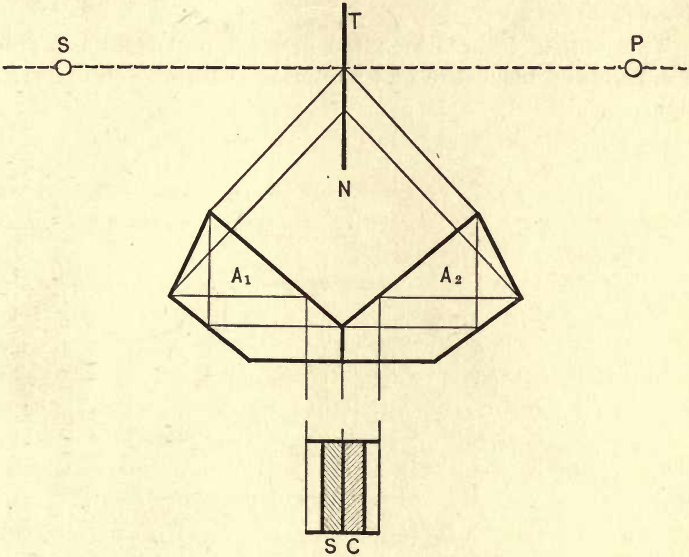


FIG. 22.

**73. The action of the optical train.**† — The diffused light reflected from the sides of the screen $l_1$ and $l_2$ falls on the mirrors $f_1$ and $f_2$, and thence is reflected along the normal to the surfaces of the triangular prisms *A* and *B*. The observer looking through the telescopic sight tube *ow* directed normally to *ac* clearly views the interior surface *arsb* of the prism *B*. The light from $f_2$ will be totally reflected to *ow* from the portions of the surface *sb* and *ar*, while that falling on *rs* will be transmitted through *A*, and will not appear in the fields to be compared. That portion of the light from $f_1$ which falls on *rs* will

* Schilling's Journal, 1884, page 587.

† Schilling's Journal, 1892, No. 29, page 573.

be transmitted through $B$ to $ow$, while the light falling on the portions $gr$ and $ps$ will be likewise reflected out of the field of vision. The observer will then view a three-part field; the central band being diffused light from $f_1$, and the other portions from $f_2$.

This optical train is mounted in a compact sight box (Fig. 23), carefully blackened on its interior to absorb the dispersed light.

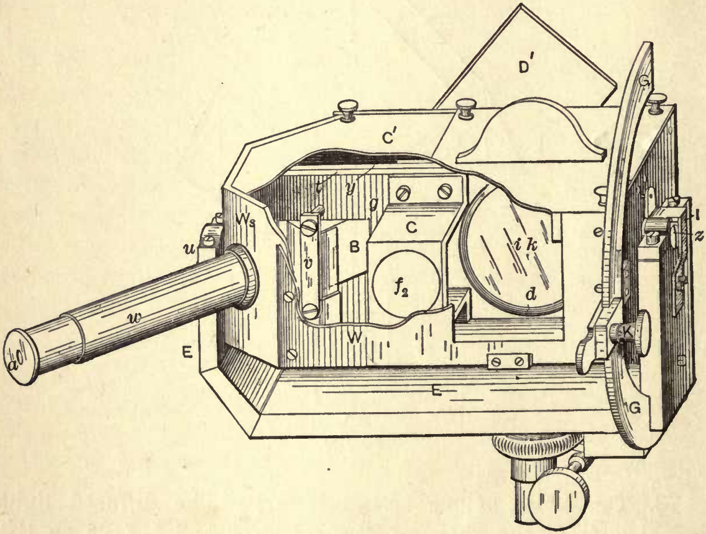


FIG. 23.

**74. The adjustment of the optical train.** — Great care and precision are required in the adjustment of the component parts, and when this is properly done, the conditions are met, that:

1. The plane of the contact surfaces at $rs$ (Figs. 24 and 25) must coincide with the plane of the screen $ik$ [or $c'd$]; or, both these surfaces and the central plane of the screen must lie in the vertical plane through the axis of the box. If this latter be taken as the plane of symmetry, then, Figure 25.

2. The reversing axis *uz* of the box lies in the plane of symmetry; and

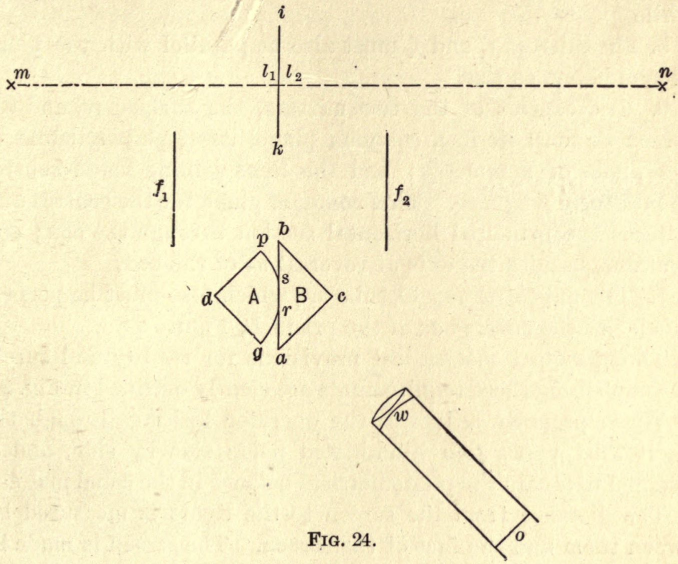


FIG. 24.

3. It passes through the centres of the contact surfaces *rs* and the screen *ik* (Fig. 24).

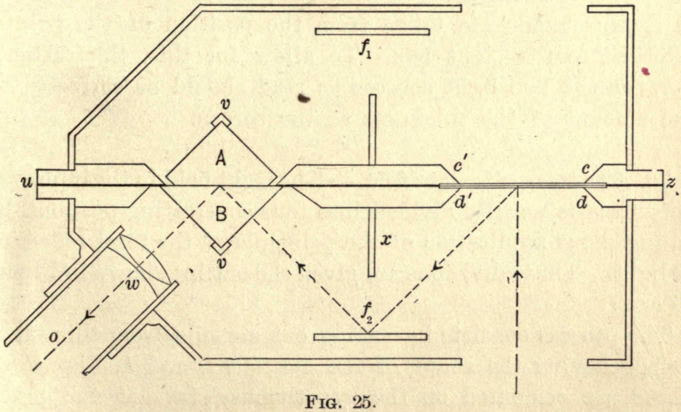


FIG. 25.

4. The edges of the prisms $A$ and $B$ must be perpendicular to the reversing axis and parallel with the plane of symmetry, while

5. The mirrors $f_1$ and $f_2$ must also be parallel with the plane of symmetry, so that

6. The centres of the two mirrors, the surface *rs*, and the screen *ik* shall lie in a common plane, itself perpendicular to the plane of symmetry; and the lines joining these centres should form a square. This common plane for the centres constitutes the principal horizontal section through the box; and contains, besides the axis of reversal *uz* of the box,

7. The axis of the sight tube *ow*, which also must be perpendicular to the surface *ac* of the prism $B$, Figure 24.

The principal mechanical provisions for readily and surely accomplishing these requirements are clearly outlined in Fig. 25.

When properly adjusted, the operator looking through the sight tube views two illuminated fields side by side, and is enabled to obtain the photometrical balance in the usual manner.

The distance from the screen to the lights is measured between them and the face of the screen. The screen is made by filling in an opening in a brass plate, about three millimetres in thickness, with calcium sulphate or magnesium oxide. The screen being so thick, an error will be introduced in consequence if measurements are taken from the position of the pointer attached to the sight box. To allow for this, the distance between the two light sources as read should be corrected by the amount of the thickness of the screen.

**75. The composite sight field.** — The sight field in the improved apparatus is usually divided into four contrasting portions, by an ingenious application of the principle of the total reflection of light. These divisions are given the outline shown in Figure 26 or 27.

The process consists in cutting out stencils from thin sheet copper having the shape of the portions $l_1$ and $l_2$, Figure 27. These are cemented on the hypothenusal face of the prism

$A$, and the unprotected portion is cut away with a sand blast to a slight depth. The hypothenusal faces of the prisms $A$ and $B$ have previously been ground and polished on each

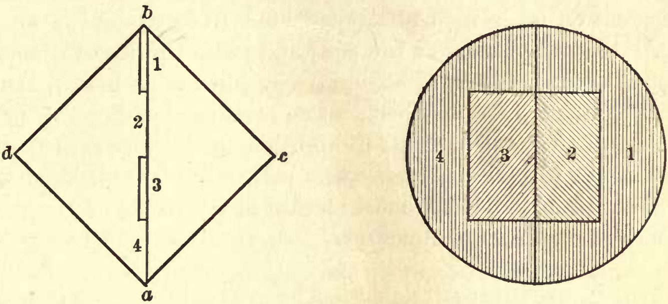


FIG. 26.

other to insure perfect contact; and after the etching is completed they are firmly clasped together, and pressure is applied until their entire polished surfaces are in contact, and are completely transparent.

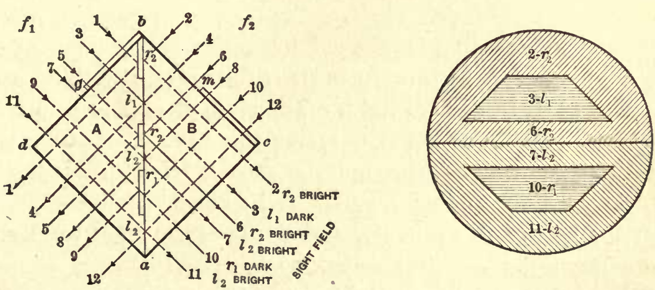


FIG. 27.

The light from $f_2$, normally incident on the face $bc$ is now totally reflected from $r_1$ and $r_2$, because the film of air back of them introduces a rarer medium in contact with the denser glass, resulting in total reflection of the light at these points which thence passes out normally to $ac$ into the sight tube.

That portion of the light, however, which falls on the faces $l_1$ and $l_2$, which are perfectly transparent, passes through and emerges from the face *ad* and is absorbed by the black coating on the interior of the sight box. Similarly, the light normally incident on *bd* is both totally reflected from $r_1$ and $r_2$ and absorbed by the coating on the box; and is transmitted through $l_1$ and $l_2$ to the sight tube. The rays of light from both $f_1$ and $f_2$ pass through the same thickness of glass in reaching the sight tube and thus suffer equal diminution by its absorption, providing the glass is homogeneous in both prisms. This ingenious sight field is one of the most elegant applications of the principles of optics to photometry.

**76. The contrast principle.***— The eye rapidly grows fatigued when viewing an equally illuminated surface, and its sensitiveness at best is low for slight differences in intensity. In an endeavour to obviate such disadvantage, the designers have introduced into this optical train a certain device which produces a well-marked contrast. This is considered especially valuable when comparing lights which differ somewhat in colour.

The contrast is accomplished by darkening the portion of the field $r_1$ and $l_1$, by interposing a thin glass absorbing strip in the path of the active light. The strip *gb* is placed in front of the face of the prism *A*, covering this to such an extent that the light transmitted through the face $l_1$ from $f_1$, Figure 27, is decreased in intensity. The strip *mc* is similarly placed over the face of the prism *B* and darkens the light totally reflected from $f_2$.

Should the comparison lights have the same colour, when a balance is obtained the symmetrical portions of the field will have the same intensity of illumination, while between these there will be a marked difference in intensity amounting to about 8 per cent, which rests the eye, and enables it to be worked at its maximum sensitiveness.

* Zeitschrift für Instrumentenkunde, 1889, page 461.

**77. Working directions.** — When the lights to be compared are of the same colour, and the train is used without the absorbing strips, adjust the telescopic sight tube until the different portions of the field are sharply outlined, the sight box being moved to a position showing considerable contrast. The sight box is then moved to a position in which the outlines of the field disappear, and there results a practically uniformly illuminated area. This adjustment is then tested by moving the sight box slightly both to the right and the left, until a distinct contrast is visible in each case. The box is finally brought back to the position of a balanced field. The setting having been noted, the box is reversed on its axis, to avoid error arising from inequality of the mirrors or screen, and the mean of the two positions is taken. Differently coloured lights can not be compared in this manner.

Or, insert the absorbing strips, and adjust the position of the sight box until a *similar contrast* is found between the central portions and the adjacent parts; that is, between $r_1$ and $l_2$, and $r_2$ and $l_1$. The dividing line between the adjoining portions $l_2$, and $r_2$, will not wholly disappear except with lights of identical colour. Since in the balanced position there is already a distinct contrast, the setting need not be proven by lateral movement of the sight box as in the preceding case. This method alone should be employed when the compared lights differ in colour. When reading the field under such circumstances, it is essential that the attention should not be directed toward the adjacent portions $l_2$ and $r_2$, but it should be given wholly to the contrast between $r_1$ and $l_2$, and $r_2$ and $l_1$, else the observer will become confused and be unable to determine a position corresponding to a balance between the illuminations from the light sources. After each setting the sight box should be reversed and a second reading taken.

**78. Certain advantages and faults of the Lummer-Brodhun optical train.** — At best it is a complicated apparatus and requires careful attention to details in its operation. The mir-

rors, absorbing strips, and prisms must be perfectly clean and the several parts be in correct adjustment. The contrast principle demands on the part of the observer, both practice and skill, especially with differently coloured lights. Should the train be employed with an equally illuminated field, the apparatus will not prove as sensitive as a well-made Bunsen screen.

For general photometrical practice the Bunsen screen is not only the simplest, but has proven the most efficient means for comparing lights which are closely similar in colour.

For purposes of investigation and in practised and skilled hands the Lummer-Brodhun Contrast Train is an admirable piece of apparatus, but will yield probably no better results than the Bunsen screen under similar conditions, except when there is a marked difference in colour to be dealt with; then the compact field, the two portions adjoining each other, presents a decided advantage. The fact that the apparatus is monocular causes the eye to fatigue rapidly and is confusing in forming a judgment of contrasts. The mirrors, too, are a fruitful source of derangement; for unless they are identical in reflecting power, neither an equally illuminated field nor equal contrasts can be obtained. In an improved form of the apparatus the mirrors are replaced with totally reflecting prisms, thus increasing not only the reliability but the sensitiveness of the apparatus.

## THE LEONHARD WEBER PHOTOMETER*

**79**. This valuable apparatus may be readily understood if it is regarded as a development of a photometer based on a transmitting diffusion screen. For this discussion, the Joly screen (page 90) of two opal glass parallelepipedons is well adapted.

* Leonhard Weber, Wiedemann's Annalen; 20, 1883, page 326; and the Elektrotech. Zeitschrift, 1894, page 166. Also R. O. Heinrichs, Transactions American Institute of Electrical Engineers; 11, 1894, page 296.

Imagine the glass block facing the compared light to be fixed in position, and its mated block to be movable toward or from the standard light. If some optical device were interposed to combine the two diffused fields into one consecutive field, the illumination from the lights could be as nearly balanced as in the accepted arrangement of the Joly screen.

Taking the distance of the fixed block from its light source as $L$, and that of the movable one as $l$ the usual photometrical law would apply,

$$I' = \frac{L^2}{l^2} I. \tag{56}$$

Further, suppose the diffusing blocks are not similar, but designedly possess different coefficients of absorption of the light passing through them. If they are calibrated to compensate for this, and their experimentally known relation is expressed by the constant $C$, and if $I$ is unity, equation 56 reads,

$$I' = C\frac{L^2}{l^2}, \tag{57}$$

which is in fact the general form of the working equation of the Weber photometer.

This apparatus consists of a tube $A$ (Fig. 28), which is mounted horizontally and is attached to a sleeve sliding on a stout post screwed into the top of the containing case. The tube contains a circular opal glass plate $f$, which is movable by a rack and pinion worked by the milled head $v$; and to this member is attached an index finger, which moves over an appropriate scale placed on the outside of the tube. The photometer settings are accomplished through this mechanism.

A lamp case slips on the larger end of this tube, in which is placed the standard light. The other end carries a sleeve upon which is centred the tube $B$, whose axis is at right angles to that of the tube $A$. The sleeve is provided with a clamping device $i$, for holding the tube at any desired angle of

inclination. A divided sector and index finger are placed here to indicate the inclination of the tube.

A Lummer-Brodhun contrast prism (page 76) is mounted in the second tube at *p*, while at the smaller end *o* is located a telescopic eyepiece for viewing the optical screen. This eyepiece is slotted to receive a slide with three circular openings; one of these is left blank while the others are filled with thin plates of red and green glass respectively. The other end of the tube is fitted with a flat and square box *g*, in which

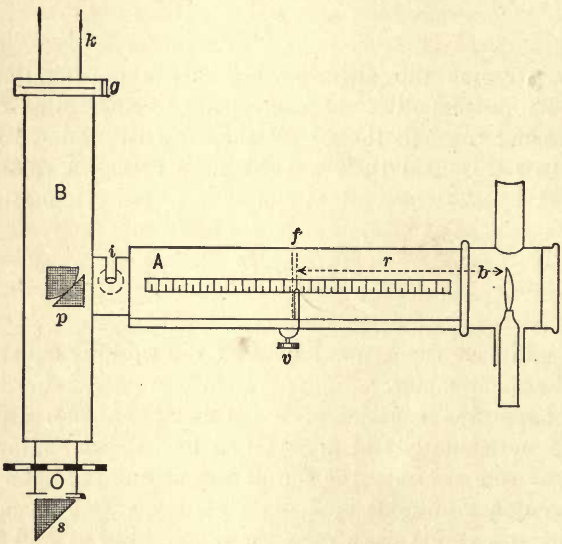


FIG. 28.

opal or coloured glass plates may be inserted, and it is surmounted by a narrower tube *k*, for the admission of the measured light.

A small prism *s* may be attached to the eyepiece to enable the screen to be viewed when the tube is pointed upward.

The standard light is obtained from a benzine lamp. The

lamp is a long and slender tube, constricted to a narrow opening for the wick. The wick is manipulated by a bent hook attached to a sliding rod. A scale and a sighting device are placed in the lamp case to enable the flame height to be adjusted with great precision.

The combustible used in this lamp is benzine, which should be as pure as possible; and since the benzine flame must itself be standardized against an amyl acetate or pentane flame, it is well, when beginning measurements with this instrument, to provide several gallons of benzine of like quality, and carefully bottle it for subsequent use. In this manner a uniform quality of the combustible will be maintained, and it will obviate frequent calibration of the flame.

The lamp is removed for filling, and after being lighted, is at once slipped into position. It should be allowed to burn for ten or fifteen minutes, when the flame will become practically constant.

When a measurement is to be made, the flame should be adjusted to a standard height of 20 millimetres with great exactness; and in all cases the precise height of the flame should be noted at the moment of measurement. A deviation of 0.1 millimetre in the height will correspondingly alter the value of the light source by nearly one per cent. A correction may be applied for any deviation within one millimetre, of one per cent for each 0.1 millimetre deviation from standard height; the correction being added for an excess over the normal and subtracted for a deficit.

A compound woven wick is used, the upper portion being woven from asbestos fibre, and it must be kept thoroughly clean. After trimming the wick, it should be lightly pressed between the fingers, and projecting fibres are to be carefully avoided.

A white screen, coated with a wash of magnesium oxide, or some similar substance, and about one foot square, is one of the included accessories. This adjunct is employed in the measurement of diffused illumination, and in determining

the constants of the instrument. When in use it is mounted on a separate stand provided for it.

The operator must be assured that the diffusing plates and the colour screen in the eyepiece are perfectly clean, before beginning the measurements.

This photometer is compact and portable, and is especially adapted for measuring the intensity of illumination from diffused daylight or from artificial sources, and as well the illuminating power of light sources. It is one of the most accurate and convenient means for exploring the illumination of large rooms or the lighting of streets.

The comparing tube $k$ may be turned to any point in azimuth or altitude, so that whatever the position of the source measured may be, the tube can readily be pointed toward it. This flexibility renders the photometer suitable for exploring the distribution of the illuminating intensity about a light source. For this purpose the photometer may be mounted on a rectangular frame (page 237) to travel about the light source as a centre; or being kept stationary, the compared light may be moved about the photometer. It may even be located as near an arc lamp under measurement as one metre, by placing additional glass plates in the slot $g$.

**80. The applications of the Weber photometer.** — There are three general cases into which the practice with this apparatus falls:

I. *The measurement of the luminous intensity of primary light sources, having the same quality of light as the benzine flame.*

A diffusing glass plate of appropriate opacity is placed in the slot $g$, and the tube $k$ is turned directly toward the light source. The position of the plate $f$ in the tube $A$ is then adjusted by turning the milled head until the sight field appears uniformly lighted to the observer, placing the eye at $O$. The distance $L$ in centimetres is then measured from the centre of the light source to the diffusing plate at $g$, and the

scale reading on the tube $A$ will state the distance $l$, also in centimetres from the plate $f$ to the centre of the benzine flame.

The intensity $I'$ of the light source, is, then,

$$I' = C\frac{L^2}{l^2} \text{ light units.} \qquad (57 \textit{ bis})$$

The value of the constant $C$ corresponding to the particular plate used in $g$, is taken from a table furnished by the maker, or it may be determined by the observer.

The value of $l$ should not be less than 10 centimetres, or the plate screen will be placed too close to the flame for accurate setting. Should a balance not be obtained with $l$ in excess of 10 centimetres, two or more plates, giving increased opacity, may be inserted at $g$. The makers provide from three to four such plates with various degrees of opacity.

The lights compared being of the same colour, the field may be viewed through the red or green glass in the ocular, or using neither, as the field can be accurately balanced in any case.

II. *The measurement of the intensity of a secondary source of illumination; the diffused light having the same colour as the benzine flame.*

(1) *By the use of the white screen.*

The tube $k$ being still in place, no glass plate is needed at $g$, as diffusion is accomplished by the white screen, unless the intensity of the illumination is too great to obtain a balance. The distance of the white screen from the instrument is not material so long as the edges of the screen lie well without the maximum cone of rays which can enter the tube $k$. This may be readily determined by removing the tube and holding it in the relative position toward the screen which it will occupy when the photometer is finally adjusted, and viewing the screen through it. The screen may be placed at any desired angle with reference to the axis of the tube $B$ so long as its obliquity does not exceed 60° from the normal to the photometer.

The photometrical reading is made as in the first case, and

the intensity of the diffused illumination, $D$, is calculated from the formula,

$$D = \frac{100^2}{l^2} C' \text{ metre-light-units.} \tag{58}$$

If the light unit used in the determination of $C'$ is the candle (English or German), the result will be in terms of the candle-metre. In any case the value of $C'$ is found by placing the standard of light 100 centimetres from the white screen. Should a balance not be obtained without a plate interposed at $g$, appropriate plates may be inserted and the corresponding constant $C_1'$, or $C_2'$, etc., employed.

(2) *A ground opal glass plate is employed instead of the white screen.*

The photometer may be made entirely self-contained for such measurements by removing the tube $k$ and placing a ground opal glass plate, usually marked $\mu$ by its makers, on the end of the tube to close the opening at $g$. The photometer is then disposed so that the ground glass plate will occupy the exact position of the white screen had it been used.

The intensity of the illumination is then given by the formula,

$$D = \frac{100^2}{l^2} C'', \tag{59}$$

where $C''$ is a new constant determined under the condition here employed; but additional plates may be inserted at $g$ as before, when the constant will correspondingly change to the value $C_1''$ or $C_2''$, etc.

The constants of a Weber photometer used in the author's laboratory were: —

I. For Primary Light Sources

| Diffusing Plate | Constant | Value of Constant |
|---|---|---|
| Number 3 | $C$ | 0.4175 |
| " 3 + 4 | $C_1$ | 1.375 |
| " 3 + 4 + 5 | $C_2$ | 3.519 |

### II. For Diffused Illuminations

| Diffusing Plate | Constant | Value of Constant |
|---|---|---|
| No plate used | $C'$ | 0.1332 |
| Number 1 | $C'$ | 0.8978 |
| 2 | $C'_2$ | 11.57 |
| " 3 | $C'_3$ | 17.64 |
| " 3 + 4 | $C'_4$ | 57.23 |
| " 3 + 4 + 5 | $C'_5$ | 146.5 |

### III. With Ground Opal Glass Plate

| Additional Diffusing Plate | Constant | Value of Constant |
|---|---|---|
| $\mu$ used alone | $C''$ | 0.7119 |
| $\mu + 3$ | $C_1''$ | 6.471 |
| $\mu + 3 + 4$ | $C_2''$ | 19.62 |
| $\mu + 3 + 4 + 5$ | $C_3''$ | 47.43 |

III. *For measurements when the colour of the light source differs from that of the standard flame.**

The illuminating power of the blue rays for purposes of distinct vision of lines or print is low in comparison with that of the other colour groups of the spectrum. If light sources then differ in colour to such an extent that they can not be directly compared, a fairly satisfactory comparison — a working comparison rather than a scientific one — may be made between their red and green colour constituents; and from these comparisons a relation may be established for expressing the

* This method is based on the investigations of Purkinje, and especially of Lépinay; "On the Photometry of Colored Lights," Annales de Chemie et de Physique, (5), 24, 1881, pages 289–337; and "The Photometric Comparison of Different Parts of the Same Spectrum," (5) 30, 1883, pages 145–214.

illuminating power of the one light source in terms of the other one.

This is admissible only when the lights compared have similar spectral groups, and the lights vary rather in the relative intensity of their colour groups. The practice of the method applies between hydrocarbon flames and the incandescent or arc lights; but can not be successfully employed between these and the incandescent gas mantles or daylight.

Either the illuminating power of a primary light source may be determined in this manner or the diffused illumination from a secondary source.

The manipulation of the photometer for differently coloured lights follows the practice already outlined. Two observations are needed: in one the lights are balanced by viewing the field through the red glass, in the other through the green glass plates in the ocular. The intensities are calculated by formula 57, as before. The intensity found by the use of the red glass, denoted by $R$, is combined with the intensity $Gr$ found with the green glass, through a factor $K$, in order to finally express the illuminating intensity sought. Thus,

$$I'' = RK. \tag{60}$$

The factor $K$ of the formula assumes a new value for each particular value of the ratio $\frac{Gr}{R}$. The relation between $\frac{Gr}{R}$ and $K$ may be determined experimentally, and tabulated for the practice of the method.

An example will make this somewhat complicated process clear. With the red glass used, a balance was obtained with a scale reading $l$, of 15 centimetres; the compared light, an incandescent lamp was placed at a distance of 100 centimetres from the plate $g$. From formula 57, with a value for $C$ of 0.33, the intensity $R \equiv I_1'$ is

$$R \equiv I_1' = 0.33 \frac{100^2}{15^2} = 14.7 \text{ light units of visibility.}$$

Similarly with the green glass $l$ was 13.5 centimetres. Then

$$Gr \equiv I_2' = 0.33 \frac{100^2}{13.5^2} = 18.1 \text{ light units of visibility.}$$

And
$$\frac{Gr}{R} = \frac{18.1}{14.7} = 1.23.$$

From a table the value of $K$ corresponding to the ratio 1.23 is 1.17. Finally the intensity sought is

$$I'' = 14.7 \times 1.17 = 17.2 \text{ light units.}$$

This number represents the measure of the illuminating power of the source, for distinctness of vision referred to the like illuminating power of the standard German candle.

Such practice with the Weber photometer gives results closely resembling those obtained by spectrophotometry, except that they are less general and exact.

These same results may be more simply and directly obtained by the use of a flicker photometer; though this photometer lacks the peculiar portability of the Weber apparatus. When measurements can be carried out in the photometrical laboratory, the flicker photometer commends itself, but for the study of light sources in their position of actual use, the Weber photometer is practically the more available apparatus.

**81. The determination of the constants.** — Though such data are supplied by the maker, they may be readily found or checked by the observer. To this end a known light source is required, whose colour is similar to that of the benzine flame. It may be a pentane or other hydrocarbon flame, or an incandescent lamp; the amyl acetate flame is too red to use directly. In any case the illuminating power of the flame employed is carefully determined by the usual photometrical methods.

If such a light source is employed according to the methods of cases I or II, the value of the constants $C$, or $C'$, etc., is found at once by solving for it in formula 57.

The value of $K$ has been calculated for the usual light comparisons,* and appropriate tables are included with a record of the constants of the photometer. While the determination of this factor is tedious, it may be accomplished in the ordinarily equipped laboratory.

The use of such an obscure factor is undesirable since all the conditions of the measurement are not within the immediate control of the observer, and results at best carry with them an element of uncertainty. No measurement can be regarded as either practical or strictly scientific until all the conditions and factors entering into it are under the immediate knowledge or control of the investigator or practician.

Lépinay † found for light sources having the same temperature but different emissive powers, a relation which is expressed by

$$\frac{I}{R} = f\left(\frac{Gr}{R}\right), \tag{61}$$

in which $I$ is the intensity of the visibility of the light source.

In order to reduce this to specified practice, he adopted standard red and green light screens and determined the real value of the function. For one set of screens this was,

$$\frac{R}{I} - 1 = 0.208\left(1 - \frac{Gr}{R}\right), \tag{62}$$

an expression from which the working values of $K$ may be calculated.

This photometer has been discussed at some length on account of its wide range of practical usefulness. No other instrument is so peculiarly adapted for measuring the intensity of powerful light sources, such as search lights and the common forms of the arc light. Its accuracy is enhanced and its range is increased by substituting a small incandescent

* An account of the determination and a table of values are given in the Elektrotech. Zeitschrift, 1884, pages 166–171.

† Comptes Rendus; 97, page 1428.

lamp of one or two candle power, operated by a portable storage battery, for the standard benzine flame. The filament should lie flat in a plane which intersects the axis of the socket on which the lamp is mounted. It must be accurately replaced in the photometer in the position it took when the constants were determined.

The intensity of such a standard lamp is readily calculated from a known standard by the use of the photometer itself, provided the diffusing constants $C$, $C'$, or $C''$ are known.

## WEDGE-SHAPED DIFFUSING PLATES

**82.** The action of diffusing plates in relation to photometrical balancing of lights has been defined in the discussion of the Weber photometer, but several interesting modifications deserve attention.

Sabine* has employed a wedge of neutral-tinted glass, $A$ (Fig. 29), for an absorption plate, which was compensated for refraction by a similarly shaped wedge of clear glass, $B$, the two being held together either by a frame or Canada balsam. This compound plate was then moved before a slot C in an opaque diaphragm by a screw motion, and its position under the slot was recorded by a suitable scale which was calibrated by working the wedge with lights of known intensity, so that the amount of absorption for any position could be obtained by reference to the scale reading.

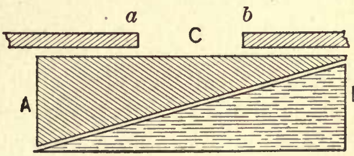

Fig. 29.

Sabine employed this device in a special form of illumination photometer, though it may be used equally well on any photometer bench.

* Philosophical Magazine; 15, 1883, page 22.

**83. The compensated wedge.** — The principle of the single absorption wedge is open to the objection of unequal action on the incident beam of light. In case the width of the opening *ab* (Fig. 29) is considerable with reference to the slope of the wedge, that portion of the light transmitted nearest *b* will be brightest, and the intensity will be regularly diminished toward *a*. If all the transmitted light were to be blended or focussed on the screen, this would have no significance aside from a probable change in the quality, due to selective absorption. The light, however, is reflected from the screen, as it is transmitted to the wedge, with the result of an unequally illuminated field.

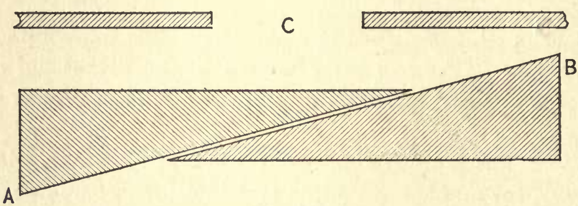


FIG. 30.

This defect is neatly corrected by Spitta* through a compensating compound wedge (Fig. 30). This consists of two wedges, similar in all respects, which by sliding, the one over the other, maintains a uniform thickness of the absorbing medium throughout the width of the slit. The action of the absorbing medium is then fairly uniform, except for a constant loss of light by reflection from the separating planes of the wedge.

THE JOLY DIFFUSING SCREEN

**84**. Very similar to the Elster diffusing screen is that devised by Joly,† though with an added optical feature which allies it with both the Bunsen and the Lummer-Brodhun

* Proceedings Royal Society; 47, 1889, page 15.
† Philosophical Magazine; 26, 1888, page 26.

screens. Structually, it is the Elster screen with the partition omitted.

The two parallelepipeds of the paraffine cube are neatly smoothed on their cut faces, and these are closely pressed together. The light falling on each half will illuminate it by diffusion. Each cut surface will reflect the light from within the mass of its appropriate half, both specularly and totally, thus rendering the slit darker and apparent. A portion of the light from each half passes across the slit into the other half. When the two blocks are equally illuminated, the reflected and transmitted lights are balanced in each, and the slit becomes invisible. The cube may be of opal glass and the two portions cemented together by Canada balsam.

When differently coloured lights are compared, the discontinuity between the diffused lights due to the slit does not wholly disappear. Though a most excellent screen for comparing lights of like tint, it has no especial advantage over other forms when the lights differ in colour. Joly mentions the advantage from viewing the slit with a magnifying glass, which enables more sensitive settings of the screen to be made.

This compound screen may be mounted in a sight box of the usual type, blackened on its interior. The dimensions recommended for the two parallelepipeds were $20 \times 50 \times 11$ millimetres.

## THE FLICKER PHOTOMETER

**85**. It has been insisted upon as one of the fundamental principles of photometry, that only the illuminations of similar colour quality could be accurately compared. While this is generally admitted, practice will frequently present occasions when lights differing considerably in tint must be compared, such as the light given by a Welsbach mantle, with that of the ordinary gas flame; or as the light from the arc with that from the incandescent lamp.

The only basis for comparison is that the lights differing in tint shall produce equally intense sensations of luminosity for

viewing fine lines or print. But this involves all the physiological and subjective difficulties already discussed.

The most successful apparatus for effecting comparisons between dissimilar lights is the flicker photometer, based on presenting to the eye, surfaces illuminated by each light source in rapidly alternating succession (consult page 18).

The apparatus may be variously arranged. A long shaft may be attached to the photometer bench, for rotating a sectored disk before each light source, the sectors being adjusted to eclipse each light in succession. Any form of screen may be used with the sectors, though a Ritchie or a Thompson wedge is especially adapted for this work.

Whitman* has designed a form of flicker photometer in which the sector is combined with the reflecting screen, and is thus movable with the sight box.

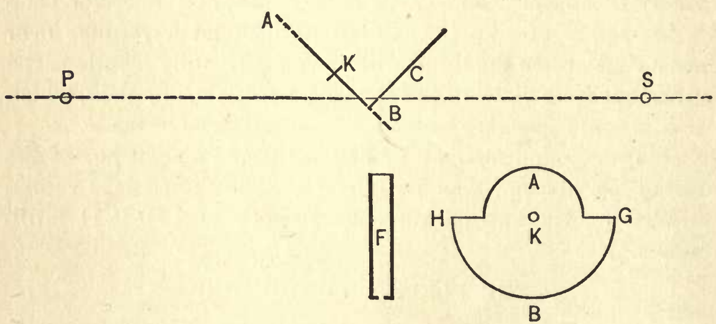


FIG. 31.

A disk *AHBG* (Fig. 31) was cut from cardboard, the radius of the semicircle *HBG* being 8 centimetres, and that of *GAH* being 5 centimetres. This was mounted on a shaft *K* attached to the sight box, and rotated before the similar cardboard screen *C*, in such position that the part *B* should eclipse the fixed screen *C* when viewed through the tube *F*.

The screen is thus in effect a Thompson wedge with one

* F. P. Whitman, Physical Review, 1896, page 241.

side only projecting. The sequence of the lights and sides of the screen is indifferent; though a notable defect of the photometer is that the screen can not be reversed. The sector may be rotated by hand or by a motor, the rotation being adjusted to that critical speed at which the illumination appears consecutive. Then, when the intensity of the illumination of the fixed and rotating sides of the screen differs, though the illumination is consecutive it will produce the characteristic flickering light sensation, which will disappear when the screen is moved to a position where the two illuminations are balanced.

Whitman, testing the precision of the setting for contrasting colours, including the whole range of the spectrum, found that such an apparatus could be used upon lights presenting the widest contrast in colour with an accuracy approaching that of the ordinary types of the photometer when balancing lights of the same colour.

Such results are only obtained with a normal eye, and when not fatigued. Should the eye be fatigued, it would show a differential sensibility toward one light or the other.

A fruitful source of error in this method arises from the Purkinje effect (page 26), though the error would be a physical rather than a physiological one.

The rapid alternations of illumination and eclipse of the screen tend to exercise the eye at its maximum sensitiveness; and for a similar reason would decrease the difference of settings, or the personal variable between observers.

In general this apparatus requires a strong illumination of the screen in order to operate it effectively.

Experiments have shown that the disk need not be equally divided; and that irregularities in the size of the opening, or the rate of rotation, are without appreciable effect on the setting of the screen. This apparatus is a development from the investigations by Rood.*

* Rood, American Journal of Science; 46, 1893, page 173; also Science; 7, 1898, page 757. Whitman, Science; 8, 1898, page 11. Ferry, American Journal of Science; 44, 1892, page 198.

A compact and highly ingenious form of the flicker photometer has recently been devised by Rood.* It is shown in plan in Figure 32. The screen, *P*, is a rectangular prism made from plaster of Paris, cast in a mould of glass plates ground to the closest fit at their juncture, that the working edge of the prism may be as sharp and regular as possible; otherwise the edge will appear in the field as a vertical black line, and of itself, will produce a faint flicker that will persist when the flicker from the faces of the prism has disappeared.

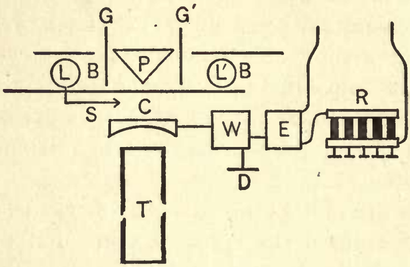


FIG. 32.

A concave cylindrical lens, *C*, in this case of 13 centimetres focus, and 4 centimetres square, is mounted on the top of an oscillating bar, and centred with reference to the plane through the apex of the prism at right angles to the photometrical axis. The oscillating bar is pivoted in the base of the photometer bench. The observing tube, *T*, is 21 centimetres in length, and 4 in diameter, and is placed coaxially with the normal axis of the oscillating lens; each end of the tube is closed with a diaphragm pierced with an aperture 5 millimetres in diameter.

The light sources compared are at *L* and *L′*; and the position of the standard light is fixed, while the compared light is moved to obtain the balance between the illuminations.

* Ogden N. Rood, "On the Flicker Photometer," American Journal of Science, 8 September, 1899, page 194; and "On Colour Vision and the Flicker Photometer," October, 1899, page 258.

The oscillating bar is moved through a train of geared wheels, *W*, actuated by a small electric motor, *E*, which is regulated in speed by means of a suitable rheostat, *R*; while *D* is a speed indicating disk provided with a number of black and white sectors, the device being adjusted to indicate the proper frequency of oscillation of the lens through the blending of the sectors.

The maximum sensitiveness of this photometer follows the adjustment which will produce the strongest flicker; and as this is dependent only on the frequency of the oscillations of the lens, the best condition results when the two illuminated faces of the prism, *P*, are just blended by the movement of the lens. Rood found a frequency of oscillation of the lens of 16 to the second would produce the maximum sensitiveness.

This apparatus is a departure in the means for producing the flicker though in all essential respects its operation follows the method already described for the flicker photometer.

The illumination of the sides of the screen was varied in quality by inserting coloured glass plates, *GG'*. In this manner a large number of experiments were made, comparing lights whose colours differed widely, with the "general conclusion drawn from numerical results that the accuracy attainable with the flicker photometer, as at present constructed, and using lights of different colours almost spectral in hue, is about the same as with ordinary photometers using plain white light, or light of exactly the same colour."

## THE ILLUMINATION PHOTOMETER OF PREECE AND TROTTER

**86.** In the various types of the compact or self-contained and portable photometers, advantage has been taken of absorption or dispersion to replace the usual method of the variation of the illumination from the standard light, by increasing the

distance between it and the screen. However, W. H. Preece and A. P. Trotter * have developed an unusually compact instrument for measuring the intensity of illumination by varying the standard illumination according to Lambert's cosine law (see page 33).

The containing case, Figure 33, is a light-proof box blackened on its interior. At the end marked *L*, two small incandescent lamps are attached, of one and two candle power at twelve volts. These are lighted by a portable storage battery.

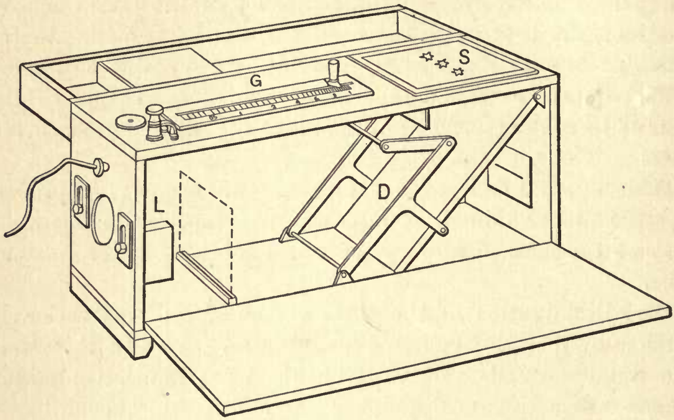


FIG. 33.

Two screens are employed; the diffusing screen *D*, and the comparison screen *S*. The diffusing screen *D* is a sheet of Bristol board, which has been moistened to remove all glaze and surface finish, and is hung at the opposite end of the box from the lamps. It is essential that this screen shall have a regular and fairly smooth surface, for at its maximum inclination when the light is incident upon it at an angle approaching 90°, the irregularities would be plainly visible and make

* Electrician (London), September 20, 1895. For an extended account consult Proceedings Institute of Civil Engineers; 35, 1883, page 39, and volume 110, page 98.

accurate readings impossible. The maximum illumination occurs when the angle of inclination is about 45°; and at this angle any glaze on the surface would produce specular reflection, leading to equally inaccurate readings. A suitable surface for the screen must be selected under these limitations, and it has been found especially difficult to meet these requirements and not depart sensibly from the cosine law.

The centre of the screen is about eleven inches from the lamps, though this dimension differs with the inclination. The screen is hinged at its upper end, and the inclination is effected by a series of levers and links operated by a handle, with an attached pointer moving over a graduated scale.

The observing screen or diaphragm $S$, is located on the top of the box immediately over the diffusing screen. It is perforated by three star-shaped openings. One opening would be sufficient, but the sensitiveness of the setting is increased by the added contrast with the two equally illuminated openings, one on either side. When the compared lights agree in tint, either the outer openings or the central one may be made to disappear, though it is designed to employ the disappearance of the central opening. When the compared illuminations are balanced, it is evident that an equal flux of light takes place in each direction.

For similarly coloured lights the diaphragm should be of the same material as the inclined screen, with the same surface tint; and when the lights are dissimilar, the screen surfaces should still be alike though they may correspondingly differ in tint. Instead of Bristol board, thin sheets of metal have given good results, painted with a wash of magnesium oxide in a solution of isinglass. For comparing the illumination from an arc light, the hinged screen may be tinted pale blue and the diaphragm a pale yellow, and in this manner the star may be made to disappear. Such an adjustment yields only approximate results, for it practically halves the error due to dissimilarity in tints between the lights, and requires an especial calibration of the scale.

The scale is direct reading, and is calibrated empirically under known standard conditions. Its intervals depart from the cosine law through the peculiar adjustment of the levers and the departure of the screen itself, for mechanical reasons, from the formal law of reflection. The scale unit is the candle-foot, and the highest reading is unity with the smaller lamp lighted, and all its indications are fractional.

Increased range is given by the use of two lamps, either of which or both may be employed; the larger one giving results of double, and the two combined of three times the direct scale values.

To operate the photometer, one or both lamps are lighted, the observer views the screen in the vertical plane of the three holes, and the handle is moved until the middle star disappears if the lights are of similar tint; or, should the lights differ in tint, the screen is moved rapidly back and forth until a new setting is obtained. The value of the illumination in the candle-foot unit (page 37) is then read directly from the scale.

**87. The illuminometer of Houston and Kennelly.*** — This apparatus was designed to measure directly the degree of illumination at any desired point. The containing case is fitted with a sight tube and magnifying eyepiece $E$ (Fig. 34), which focusses on the inclined surface at $B$ carrying the test object, which may be white paper with printing or drawing upon it. The test object is illuminated through the opal-glass window $W$, while the effective area of the window is controlled by the sliding shutter $S$, whose movement is indexed along an appropriate scale.

The eyepiece having been focussed, the shutter is opened until the test object becomes clearly visible, when the degree of illumination may be read directly from the scale. Instrumentally, the degree of illumination is a function of the effective area of the opal glass window. The scale is calibrated in the photometer dark room, from a light whose illuminating

* Electrical World; 25, 1895, page 309.

power is known, by placing the apparatus at measured distances and marking the position of the shutter at which the test object becomes visible. The scale unit is then the candle-metre (page 37).

Owing to the fatigue of the eye, there will be some discrepancy in the readings made by obscuring the window from full illumination until the test object disappears, as against readings made with the reverse process.

In principle, the illuminometer is a photometer in which the intensity of the measured illumination is compared with a standard one, — that under which the scale was calibrated.

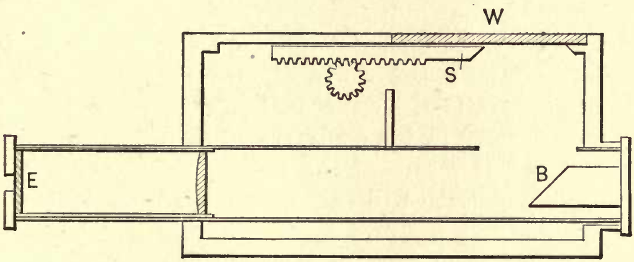


FIG. 34.

The vanishing point for distinct vision is neither constant in any one eye, nor is it the same between different eyes. The sensitiveness of the eye, too, for very weak light is low, and these two causes render the readings of the instrument indicative rather than quantitative. The designers suggest that the mean error is about ten per cent.

**88. The relative sensitiveness of photometer screens.** — Comparative data of the sensitiveness of different screens are to be taken as suggestive rather than final. So much depends on the subjective states of the observer as well as the care in adjusting lights to equal tints, upon which condition the comparison is based, and to the maintenance of the lights at constant intensities.

The results of tests by the Netherlands Gas Commission,* apparently made with great care, are of value. This Commission found the average settings to depart from a true mean value by

| | | Per Cent |
|---|---|---|
| 1. | For Bunsen Photometer, ordinary form | ± 0.08 |
| 2. | Foucault Photometer | ± 0.32 |
| 3. | Lummer-Brodhun Optical Screen | ± 0.52 |
| 4. | Bunsen Photometer with reflecting prisms | ± 0.25 |

## VARIOUS PHOTOMETERS AND PHOTOMETRICAL DEVICES

**89. The dispersion lens.** — A concave lens placed in the path of the light from a source will disperse it over an increased surface, whose ratio of increase of area over that which would have been covered by the unobstructed light is determined by the radius of curvature of the lens. The intensity of the resulting illumination will vary inversely with the amount of the dispersion.

The method is apparently a simple one and of value in photometrical measurements, but in practice several sources of error have proven the method an unsatisfactory one. Except for purposes of investigation, it is now seldom employed, and its lessened importance does not warrant a full discussion of its theory in this connection. Absorption plates, and especially the revolving sector, are more suitable and practical means for diminishing the intensity of the radiations from a light source. The objections to the use of the dispersion lens arise from reflection of light at the surface, spherical aberration, and absorption by the glass.

**90. The dispersion photometer of Ayrton and Perry** † was formerly employed to a considerable extent, but it offered

* Schilling's Journal, 1894, page 617.

† Philosophical Magazine; 14, page 45.

numerous sources of error, and has in consequence been displaced by more accurate apparatus. However, it has been so widely known that a brief description will be given.

The photometer mounts a biconcave lens in the frame *C* (Fig. 35), movable along the slide *F*. A reflecting mirror *H*, is fastened to an axis at a fixed inclination of 45°, and enables the light from a source placed at any elevation to be measured without introducing an error arising from absorption at varying angles of reflection. A graduated circle *G*, measures the

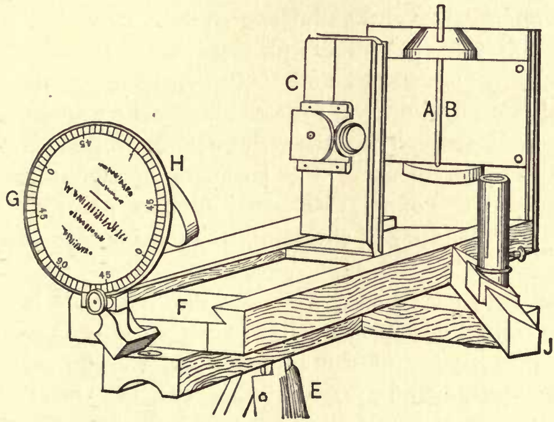


FIG. 35.

angular elevation of the light source. A standard candle is placed in a case which prevents its light from falling on the side of the screen nearer it; the containing case is movable along the bar *J*. The comparison of the illuminations is accomplished by means of a Lambert screen, a thin black rod being mounted in front of a sheet of white paper *AB*.

The distance *D*, of the compared light is measured to the centre of the mirror *H*, and thence to the screen. The distance *d*, of the lens from the screen is noted as well as the distance *c*, of the standard candle. The focal length of the lens being

$f$, the intensity $L$, of the compared source is found from the formula given by the designers,

$$L = \frac{1}{c^2}\left\{D + \frac{d(D-d)}{f}\right\}. \tag{63}$$

The tedious calculations involved in this method greatly interfere with the general utility of the apparatus. The formula contains no correction factors for the reflection and absorption of the light by the lens, and at best can only be an approximation.

**91. The intensity of the illumination in terms of the energy.** — The complicated nature of photometrical observations has already been emphasized and their dependence on combined physical and physiological events. An analogy was instituted in Chapter I (page 3) to show the desirability of an entirely physical measurement of the intensity of the light source, which should also express its visual intensity; and the present seeming impossibility of obtaining this consideration was dwelt upon.

A number of noteworthy attempts, however, have been made to accomplish this; but they have resulted only in a measurement of the energy of the illumination, and no satisfactory factor has been found to connect this with the visual effect, or to translate these results into what is known as the intensity of the illumination.

**92. The selenium screen** is such an attempt. Light falling on selenium changes its electrical resistance to an extent ascertained by Adams * to be

$$\textit{Resistance of Selenium} \propto \sqrt{\textit{Illuminating Power}}.$$

Such a screen, standardized by reference to a known light source, may be mounted on the photometer bench in the usual manner.

* Proceedings of the Royal Society; 28, 1876, page 163; also Proceedings of the Institute of Civil Engineers; 44, 1876, page 169.

**93. The bolometer** * is an apparatus which in its action closely resembles the selenium screen. The essential portion of the apparatus is a very thin wire, usually of iron coated with carbon. When exposed to light it becomes heated, and the change in its electrical resistance affords a means for measuring the energy intensity of the incident light.

**94. The Crookes radiometer,** shortly after its development, was investigated as a probable means for measuring luminous intensity. The propulsion of the vane from light absorbed on its alternately blackened faces, is seemingly a direct mechanical means for photometrical measurements. Pedler,† investigating it for this purpose, found that the temperature of the air produced such marked changes in the rate of rotation of the vane, that from this cause alone it would not prove a practical apparatus.

**95. Chemical photometry.** — Numerous attempts have been made to define the illuminating power of a light source in terms of its activity in producing certain chemical decompositions. The chemical action of light is largely due to the ultraviolet or actinic rays, which are invisible. A light source may possess a high illuminating power and yet be very feeble in actinic qualities; and conversely, an actively actinic light source may have a disproportionately low illuminating power. There being no essential connection between the proportion of the actinic rays and those producing illumination, the application of the chemical action of light is of no particular value in photometry.

Draper ‡ in 1859 endeavoured to measure the intensity of daylight by its action on a solution of peroxalate of iron and

* For a description of the bolometer and its application to photometrical measurements consult Transactions of the American Institute of Electrical Engineers, 13, 1896, page 137.

† London Journal of Gas Lighting; 36, 1880, page 335.

‡ Philosophical Magazine; May, 1859, page 91.

perchloride of gold. The time-rate of the formation of a finely divided precipitate of gold was taken as a function of the luminous intensity of the light. An apparatus based on such principles would be an actinometer rather than a photometer.

## THE PHOTOMETER BENCH

**96.** The mounting of the screen and its containing sight box and the light source, varies in practice according to individual requirements, and it is a matter that may be left to the design of the experimenter. The essential for the proper mounting of the photometrical train is a track or way along which the sight box may be readily moved in a plane parallel with the photometrical axis. One or two scales should be provided; an equably divided one giving the distance from the screen to each light source; the other stating the setting of the screen directly in light units. The supports for the light standard and the compared light should admit of ready adjustment of the height of the light sources.

Of a number of excellent commercial photometer benches, perhaps the best known is a type designed in connection with the investigations at the Physikalische Reichsanstalt.

**97. The Reichsanstalt photometer bench** is commonly made for a maximum working distance between the light sources of either 200 or 250 centimetres. The sight box (Fig. 36), supports for the lights, and accessory apparatus are mounted on separate carriages which may be readily moved or adjusted along a track or clamped in a desired position. The track consists of two hollow steel tubes some 35 millimetres in diameter, and separated by a distance of 12.5 centimetres between their centres. The rails are carried by two cast-iron end frames and a central or stiffening frame. One, and in some cases two, similar tubes are placed below the parallel ones for tie rods. This construction insures a stiff and at the same time a light and effective mount. The frames are fitted with

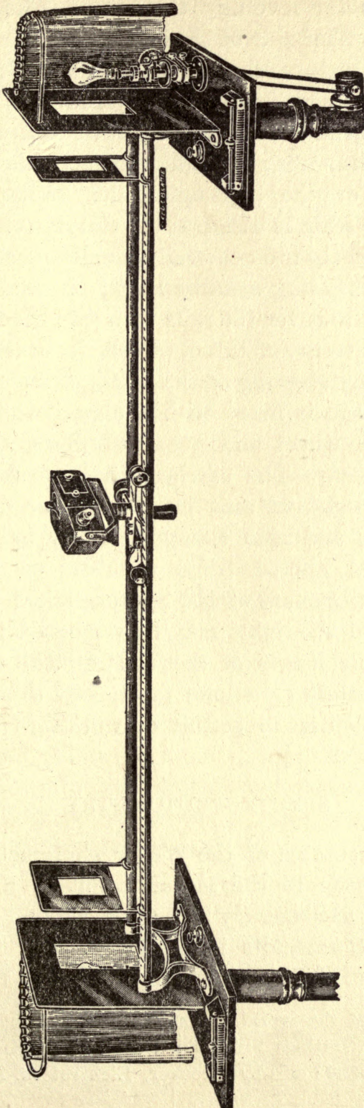

FIG. 36.

adjusting screws for levelling the track. The experimenter may work from either side of the bench.

The entire structure should be coated with a dull black lacquer, excepting a narrow band on each rail; this is silver plated and engraved with a scale. One rod carries a scale graduated in millimetres; the other one may have engraved on it a candle power or other light-unit scale. In imported benches the candle power scale is based on the German candle. Where the carriage wheels bear on the rails, the lacquer will soon wear off, exposing a reflecting metallic strip; an attempted remedy for this has been to cover the rails with thin hard rubber tubes.

Each carriage rests on three wheels in order that it may adjust itself to any skewing of the bench or inequalities in the rails. The carriage is fitted with a clamp which grasps the rail between the wheel and a curved plate, and is quickly applied or removed. The carriage base carries a socket in which slides a post that may be elevated or depressed by a rack and pinion, and also clamped at any height; to these posts the several photometrical members of the train are attached. The alignment of the photometrical train is easily accomplished, and the lights may be separated to any desired distance up to the length of the rails.* The bench may be mounted on pedestals or a long table, and this should be so placed in the room as to permit of working freely on either side.

## SPECTROPHOTOMETRY

**98**. In the discussion of the Weber photometer (page 85) a reference was made to the measurement of a light source, viewing the field successively through a red and a green glass, and combining the results in such a manner that the total illuminating effect of the source was stated as a function of the

* The influence of the working distance of the light sources on the sensitiveness of the settings has been developed by Krüss; Schilling's Journal, 1886, page 890; and by Strecker, Elektrotech. Zeitschrift, 1887, page 17.

measurements obtained with these two screens. This method is pregnant with suggestion for the solution of some of the vexed questions in the photometrical comparison of light sources, and the illuminating value of any particular source.

The extension of such a method leads to a class of measurements whose object is the comparison, not only of the red and green, but of all the constituents of the light quality by means of a photometer, which shall include in its optical train some form of spectroscope. The necessary apparatus, however, is complicated, and its practice belongs rather to the physical laboratory.

Spectrophotometry can not, in its present development, be considered a branch of applied photometry, though it may eventually become such should a rational standard of light quality be adopted based upon its physical analysis. The apparatus and methods for the prosecution of spectrophotometry are so varied, and the literature of the subject is so extensive, that it does not admit of treatment in this discussion.

Briefly, in spectrophotometry a spectrum of each of the two light sources is viewed, the one appearing located above the other to the observer. These spectra should be separated from each other by a very narrow dark band with sharply defined limits, and they are adjusted relatively, so that corresponding colour bands or wave lengths appear one over the other. The act of measurement then consists of taking the spectra, colour by colour, or wave length by wave length, and adjusting either the distances of the lights or the position of the spectroscopic sight box, as the case may be, until equal intensities in the colour groups are obtained. If this is done for the principal colour groups of each spectrum, not only will the quality of each light source be known, but the relative intensities of the light constituents.

It is seldom that two light sources will show identical quality; and as a rule they differ not only in quality or colour constituents, but in the relative intensity of these constituents.

The illuminating power of any light source, then, is defined between these two variables, and a truly scientific expression of the illuminating power would follow from a modification of a method used by Maxwell.* The illuminating power of each light constituent being known, the total illuminating power of the light source would be a function determined by securing the illuminating powers of its constituents.†

* Consult Rood, Text-book of Color, pages 120 and 224.

† For an outline of the apparatus and practice of spectrophotometry consult Manual of Applied Physics, Nichols, Vol. II, Chap. IV. For an application of this method of investigation see an article on the spectro-comparison of Auer gas mantles with arc and incandescent lamps by Mützel, Electrotech. Zeitschrift, 1894, page 476.

# CHAPTER IV

## STANDARDS OF ILLUMINATING POWER

**99. Illumination distinguished from illuminating power.**—The ordinary acts of vision are excited through light which is reflected from surfaces into the eye. This gives rise practically to two lines of investigation: (1) The influence of the surface upon the quality of the light falling upon it, and the percentage of the whole light which is reflected from the surface. Such phenomena come within the scope of a work on illumination, in which, however, photometry may be employed as a means of measurement. And (2) the character and intensity of the effect which a source of light exerts directly or indirectly on the eye. Photometry deals with the measurement of these effects. These two classes of phenomena are always related when the eye is excited through reflected light.

In general, any surface from which the eye is excited to acts of vision is in a sense a light source; and a primary light source is one which radiates light from its surface, while a secondary light source reflects the light from its surface.

The function of photometry, then, is the measurement of the illumination from reflecting surfaces, and the illuminating power of radiating sources.

It is obvious, too, that the illumination from reflecting surfaces is ultimately dependent upon the illuminating power of light sources, and that, in establishing units and standards for photometrical measurements, there will necessarily be certain fundamental units and standards of illuminating power.

**100. Basis for photometrical standards.** — A standard of illuminating power is not primarily a physical standard of light. It was emphasized in Chapter I that photometrical standards must rest primarily on a physiological basis. Here occurs the confusion in many discussions of these subjects. It has been advanced that standards of illuminating power are not possible, since colour and light sensations are not stimulated to the same degree in all normal eyes by sources of the same intensity and quality, even though all such eyes perfectly agree in the power to discriminate colours and colour shades.* This consideration is not only confusing, but foreign to the subject of standards of illuminating power, for experimental data show that different normal eyes vary in the intensity rather than the quality of their sight sensations. As a consequence of Fechner's law, it is not the magnitude of the sight sensation which is to be measured in photometry, but the magnitude of the stimulation.

The true basis for standards of illuminating power was indicated in Chapter I. This basis was found to be empirical, and its character was defined by the investigations of Young, Helmholtz, Maxwell, and others.

**101. A fundamental standard of illuminating power impossible.†** — In order to reduce the physical properties of ether waves of any frequency to a fundamental standard expressed in centimetre-gramme-second measure, it is necessary to establish for them an invariably constant and measurable effect. But such an effect must be purely physical in order to be constant, as the heating effect on a blackened surface. When it has to deal with the illuminating power of ether waves, the eye, in a sense, behaves toward them like a galvanometer toward the electric current. But the eye, as a metering instrument for light, does not give an unvarying result for the same amount and character of stimulation, as was pointed out in the

* Compare a suggestion by Abney, British Association Report; 1883, page 424.

† Consult Blondel, "The Continuous Current Arc," Proceedings International Electrical Congress; 1893, pages 316–317.

discussion of Fechner's law (page 15). An empirical, and to some extent arbitrary, standard only is possible, and when this is once adopted and defined, it can be ultimately reduced to fundamental centimetre-gramme-second measure of heat waves; but this will in no sense define the illuminating power.

**102. The ideal photometrical standard.** — The mechanism of the various photometrical screens and benches has reached a high state of accuracy and perfection, and far excels in these respects all known standards of illuminating power. The errors and uncertainties in photometrical measurements originate in nearly all cases from unsatisfactory light standards. Probably no one subject in physical measurements has received more painstaking investigation, but the results so far obtained are all far from satisfactory in their ability to establish a standard of illuminating power. The importance is then apparent of an attempt to obtain a clear conception of the properties of an ideal standard in photometry.

A satisfactory empirical standard must emit ether waves of such frequencies and intensities as shall excite the primary colour sensations of red, green, and violet, as indicated by data obtained from experiments. The curves given by Helmholtz and confirmed by Maxwell (Fig. 4, page 14) may be accepted as rational until further investigation shall indicate their improvement. The ideal standard, then, would conform to these curves, and its conformity could be accurately measured by means of the spectrum photometer.

None of the photometrical standards now in general use conforms to these requirements. As a rule, each unduly emphasizes either the red or violet colour group. Carbon, heated to a certain high temperature, appears to fulfil these conditions with satisfactory exactness, as in an incandescent lamp exhausted until the blue glow disappears. As yet this particular temperature has not been exactly determined. The acetylene gas flame, on account of the whiteness of its light, also promises well as a standard flame.

**103. Requirements for the photometrical standard.** — In addition to the optical properties just considered, a practical standard should fulfil the conditions: —

1. Simplicity of construction and operation.
2. Reasonable permanence of its parts.
3. Reproducibility with accuracy.
4. Constancy in operation.

**104. The practical unit of illuminating power.** — There is no generally accepted national or international unit of illuminating power. In the United States and in England the prevailing unit is the candle power based on the spermaceti candle; in Germany another candle-power unit is in general use, but this is based on the paraffine candle (Vereinskerze); while in France the accepted unit is the carcel, based on a peculiar argand lamp of that name.

The photometrical unit must eventually be arbitrarily chosen, and may or may not be the value of the standard of illuminating power. Though as the standards more nearly approach the theoretical requirements, it is obviously absurd to continue to evaluate them in terms of an imperfect unit such as the carcel, or candle power, especially since by all rules of enumeration the unit should be of the same character as the standard.

**105. The luminosity of flames.** — This subject is one which presents many difficulties and obscurities, and though frequently investigated, the results obtained are widely divergent.

For the purposes of photometry a general outline of flame phenomena may be given. When the combustible is either solid or liquid, a wick is employed to feed it to the flame. The liquid combustible — for if a solid, it is melted by the heat of the flame — passes through the wick by capillary action at a rate determined by the physical conditions which influence the capillary action. Gaseous combustibles are supplied to the flame under regulated pressure through an opening in a tube. The combustible in any case consists chiefly of hydrocarbons,

compounds of carbon and hydrogen, singly or in combination with compounds of carbon, hydrogen, and oxygen.

A flame consists of three principal cones or layers. In the inner one the combustible is heated and undergoes decomposition, and no light is emitted from it. In the central layer carbon and very dense hydrocarbons are liberated, which being heated to incandescence constitute the principal source of luminosity. In the outer layer the oxidation of the carbon and hydrogen is completed, and this layer feebly contributes to the light emitted by the flame by means of incandescent gases and vapors. A flame, briefly, is the seat of exceedingly complicated chemical reactions delicately balanced and subject to sudden and marked variations, and is as well the focus of streams of cooling and diluting gases from the surrounding air.*

**106. The influence of variations of atmospheric pressure on the luminosity of flames.** — In 1859 Frankland and Tyndall made some interesting experiments to determine the influence of high elevation on the rate of consumption of the combustible, and the luminosity of the flame.† They found the amount of combustible consumed per hour was practically unaffected by the pressure of the air, and with the low atmospheric pressure which occurs at the top of Mt. Blanc the candle flame became as non-luminous as that of the Bunsen burner.

Frankland subsequently extended these investigations and found, in general, that on decreasing the air pressure even a smoky flame burns clearly, and tends toward the low luminosity of the Bunsen burner; while by increase of pressure an alcoholic flame, too, becomes white and luminous. Frankland concluded that "the variations of illuminating power depend chiefly, if not entirely, upon the ready access or comparative exclusion of atmospheric oxygen as regards the interior of the

* An interesting discussion of the luminosity of flames was given by Professor Vivian Lewes in his London Institution lectures. Consult the Scientific American Supplement, April 2, 1892, page 13,544.

† Heat as a Mode of Motion, Tyndall, page 64.

flame."* With decrease of pressure the flame became more permeable to the surrounding air, and the combustible being more completely oxidized and diluted, the flame correspondingly decreased in luminosity.

**107. The influence of the height of the flame on the illuminating power.** — This aspect of the investigation of light standards has received marked attention,† and the data are both voluminous and widely divergent. Whatever may be the gas-producing power of a combustible, either solid or liquid, there is a critical flame height which may be taken as a normal one for that illuminant, and it is seemingly influenced by the rate at which the atmospheric oxygen penetrates the flame. A flame increasing toward the normal height grows hotter and the decomposition of the combustible is more active. When the normal height is exceeded, the incomplete supply of oxygen produces rapid lengthening of the flame. The changes of flame length would then be greater both below and above the normal height.

It has also been established for practically all flames, that the illuminating power varies proportionally with the flame height for limits of at least $\pm$ 5 per cent on either side of the normal height.

**108. The effect of moisture on the luminosity of flames.** — When a chemically inert gas or vapour is introduced into a luminous flame, there generally results a marked diminution of its illuminating power, though experiments have not so far shown conclusively in what manner the diluting substance affects the flame, other than to reduce and alter the light emitted. In this way non-combustible constituents of the atmosphere, such as aqueous vapour and carbon dioxide, may be expected to influence the light values of all flames; and as the proportions of these substances vary so greatly from time to time, they must introduce error and uncertainty in flame measurements.

* Philosophical Transactions; 1861, page 652.

† Probably the most thorough investigation has been made by Hugo Krüss, Schilling's Journal, 1883, page 511.

## THE ENGLISH CANDLE

**109.** A committee of the British Association reporting in 1888 on light standards* stated, "The present standard candle is not worthy in the present state of science of being called a standard." In detail its faults were specified to be uncertainty in the composition of the spermaceti and the weaving of the wick; the fluctuations in the flame from the variations in the length and form of the wick while burning, and the filling and emptying of the cup of the candle. These conclusions were based on an extended series of measurements performed with unusual accuracy and care.

The untrustworthiness of the candle to serve as a standard of light has been recognized from the earliest practice of photometry. Various investigators have examined it with more or less thoroughness, and always with the result so clearly and authoritatively expressed in this report of the Committee of the British Association.

**110. The character of the light.** — Aside from all considerations of the constancy of the illuminating power of the candle, the quality of its light would render it unsatisfactory as a standard. Candle light does not excite the eye normally; the light is too red, and is deficient both in the extent and relative intensity of the violet colour group. In consequence, it is unable to bring out the full values of colours in which greenish blue, blue, or violet shades are constituents. Under the ordinary conditions of burning, the character of the flame does not permit sufficiently high incandescence of the free carbon contained in it to emit, in normal proportions, those wave frequencies belonging to the violet colour group.

* Proceedings British Association, 1888, page 39 (Reports). For a clear statement of the events in the burning of a candle, consult "The Chemical History of a Candle," by Faraday, especially Lectures I and II.

**111. Description and specifications.*** — The finished candle is ten inches long, and is 0.9 inch in diameter at the bottom, and tapers slightly to 0.8 inch diameter at the top. The wick should be made of three strands of cotton plaited together, each strand consisting of eighteen threads. The strands should be plaited with such closeness that, when the wick is laid upon a rule and extended by a pull just sufficient to straighten it, the number of plaits in four inches should not exceed thirty-four nor be less than thirty-two.

The wicks should be steeped in a liquid made by dissolving one ounce of crystallized boracic acid in a gallon of distilled water to which two ounces of liquid ammonia have been added. The wicks are then to be pressed until most of the liquid has been removed, and dried at a moderate heat. Twelve inches of the wick thus made should not weigh more than 6.5 nor less than six grains. The weight of the ash remaining after the burning of ten wicks which have not been steeped in boracic acid, or from which the boracic acid has been removed by washing, should not be more than 0.025 grain.

The spermaceti of which the candles are made should be extracted from crude sperm oil, and it should be so refined that it has a melting point lying between 112° and 115° Fahr. Since the candles made with spermaceti alone are brittle, and the cup which they form in burning has an uneven edge, it is necessary to add a small portion of beeswax or paraffine to remedy these defects. The best air-bleached beeswax melting at about 144° Fahr. is to be added to the spermaceti in proportions of not less than three per cent and not more than 4.5 per cent.

The candles made with the materials above described should weigh, as nearly as may be, one-sixth of a pound. As the rate of burning of a candle is affected by the force with which the wick is pulled when it is set in the mould, the strain commonly applied by the careful maker is found to be about twenty-four ounces.

* The full text of the specifications issued by the Metropolitan Gas Referees may be found in American Gas Light Journal; 60, 1894, page 41.

The wicks, before steeping, should be washed, first in distilled water made alkaline with one or two per cent of strong liquid ammonia, then in a ten per cent solution of nitric acid; and finally should be thoroughly and repeatedly washed in distilled water.

**112. The influence of the state of the combustible.*** — The composition of the wax of the sperm candle is always more or less uncertain. Owing to difficulties in separating the spermaceti from the sperm oil of which in the crude state it is a constituent, the solid spermaceti invariably contains more or less oil whose effect is to increase the luminosity of the candle flame. As the processes for the separation of the spermaceti have improved, the wax has become "drier," and the luminosity of the standard candle has been observed to decrease proportionately. Another element of uncertainty is introduced in the small amount of beeswax which is added to the spermaceti to overcome its tendency to crystallize.

**113. The influence of the wick.** — The exposed portion of the wick, as it increases in length when the candle is burning, usually becomes curved and deforms the flame, especially at its base. Methven † found a maximum change in candle power from this cause alone of four per cent; and that the best average candle power was obtained when the plane of the curvature of the wick was at right angles to the plane of the screen, the wick being curved from the screen. As the wick curves, it deforms the flame, and by displacing the centre of the light source, has the effect of changing the length of the photometer bar. The charring of the wick influences the capillary flow of the melted wax to the flame, and this disturbance is not without its effect on the candle power of the flame. The wick is usually treated in a dilute solution of an alkaline

* Consult "Soaps and Candles," W. L. Carpenter, Chapter XII, and especially page 240.

† London Gas World, Nov. 30, 1889, page 597.

borate, or similar substance, to cause a fusion of the ash. Besides modifying the action of the wick such substances impart a slightly greenish yellow tinge to the flame.*

The size of the wick is of significance, governing, as it does, the amount of the combustible consumed. It is so designed in thickness and weave that it will supply 120 grains per hour under the ordinary conditions of burning.

The height of the flame is dependent on the length of the wick above the melted wax in the cup. With a flame burning uniformly and undisturbed, the cup will form with an even rim and the melted wax will not escape. But should the side of the cup be melted down and the contents escape, the length of the exposed wick is considerably increased.

**114. The normal flame height.** — This is now accepted to be 45 millimetres, and it is practically necessary to take the measurements of candle power at this particular height, for only very approximate corrections can be applied. When this height is exceeded, the wick must be snuffed, and in order that the flame may be steady at the normal height for even a short time, the snuffing of the wick must be done with care, and frequently repeated, removing but a little at a time.

The measurement of the flame height is rendered difficult through the rapid movements at the base of the flame, and the feeble luminosity of this portion. The height may be observed by means of a suitable cathetometer or a reading telescope and a vertical scale † placed close to the flame; or an image of the flame may be projected on a screen and directly measured.

**115. The influence of air currents.** — All open flames are extremely sensitive to disturbances in the air about them;

* Other specifications require the wick to be thoroughly washed in distilled water, then treated with a 1 to 2 per cent solution of ammonium hydrate, followed by immersion in a ten per cent solution of sulphuric acid, and a final washing in distilled water.

† Hugo Krüss, Schilling's Journal, 1883, page 717, describes a compact instrument of this character for measuring flame height.

and while urging objections of such a nature against the candle, it must be granted that the effects of mechanical disturbances on the flame itself are the same for all unprotected flames. Even a slight movement of the arm while adjusting the screen may cause the open flame to waver.

One of the greatest difficulties in the use of the candle is to maintain a steady flame; and such flames are practically suitable for measurement only during short and infrequent intervals, for the air of a room is continually disturbed by currents caused by the unequal temperature of the walls and floor, drafts, and the convection currents set up by the flame itself.

If a candle flame is blown to one side by a draft, heated air is directed against the walls of the cup, and they are apt to yield and allow the melted wax to flow out. This lengthens the wick, with a corresponding increase in flame height. An inopportune draft, when all conditions for reading the screen are normal, may lose the reading to the observer and necessitate a renewed trimming of the wick, and a repetition of bringing the standard up to normal conditions. A draft will also change the balance of the chemical reactions in the flame, by affecting the decomposition and the rate of oxidation of the combustible.

There is no efficient protection for open flames against air currents. When a candle flame, for instance, is enclosed in a box, unless it is a very wide one, it will induce drafts, and these, by increasing the oxidation-rate of the flame, will reduce the luminosity. The same action is greatly intensified by the use of a chimney.

**116. The influence of moisture in the air.** — The degree of humidity of the atmosphere in which a candle is burned proportionately reduces its illuminating power. Methven* found with a constant weight of candle burned, 120 grains per hour, that the luminosity decreased as much as 8.4 per cent due to moisture in the air. A candle consuming 120 grains in one hour in dry air gave 1.196 units, and while burning in moist

* London Gas World, Nov. 30, 1899, page 598.

air under the same conditions of flame height and consumption it gave only 1.104 units of illuminating power.

**117. The influence of air pressure.** — Though Frankland has shown the general influence of the variation in air pressure on the luminosity of the candle flame (page 113), more exact determinations are not necessary. At any given pressure the variations in the illuminating power of the candle are so great and uncertain that it is unnecessary to attempt to introduce a correction for changes in the atmospheric pressure.

**118. The time variations of the flame.** — Summing up the many causes of variation in the illuminating power of the candle flame, it is evident that the fluctuations will not only be large in amount, but will occur rapidly. Were such a flame, even under a certain set of conditions, suitable for a light standard, these would change so quickly that its value as a standard would be seriously impaired. All this may be made evident by watching a candle burning in a darkened room. Some painstaking experiments have been carried out in an endeavour to show these changes graphically.*

**119. Requirements for unit candle power.**† — The spermaceti candle is supposed to emit unit illumination when consuming 120 grains of combustible per hour, at a flame height of 45 millimetres, while burning in dry air under normal atmospheric pressure.

**120. Directions for the use of a standard candle.** — In the course of this discussion of the English candle many considerations have been established which point to the non-use of the candle

* Physical Review, Vol. II, page 1; also Transactions American Institute of Electrical Engineers, 1896, pages 133–205. These methods are based on the supposition that the heat radiated from a flame and the illumination it emits are in a constant ratio; a proposition of no real photometrical value.

† For recent specifications for the English candle, consult an article by E. G. Love, in the American Gas Light Journal, March 5, 1894, page 326.

as a light unit for photometry. The references given are deemed sufficient for the needs of investigators, yet it may be desirable to recapitulate briefly such directions as should be observed when the candle is used. The candle should be allowed to burn for at least fifteen minutes before taking any measurements with it. The flame should not be enclosed in either box or chimney. Finally, when the top of the candle is well cupped, the wick is trimmed, and the flame length observed as it increases, and when this is 45 millimetres, the position of the screen is read. The disturbing conditions and the precautions to be taken in connection with these must be carefully observed.

### THE GERMAN CANDLE (VEREINS NORMALKERZE)

**121. Description.**—This light standard was adopted in 1869, and definitely specified by a Commission of the Gas and Water Works Association of Germany in 1871.* These specifications were unusually minute, and applied to the material and methods of manufacture, and directions for the use of the standard.† In order to insure uniformity in their manufacture, the candles are made under the supervision of a commission of the association, and are supplied by the association under a guarantee that they fulfil the specifications for the combustible, the wick, and the size and weight of the finished candle. It is accordingly named the *Vereinskerze.*

The specifications require a twisted wick of 25 cotton threads, one metre of the finished wick weighing 668 milligrammes. The candle has a uniform diameter of 20 millimetres, and when of the standard length of 314 millimetres should weigh 83.6 grammes. The same elaborate attention is paid to cleansing the wick as in the manufacture of the English candle.

* Schilling's Journal, 1869, pages 364 and 521, and succeeding reports of the Commission for Light Measurements.

† The full text of the specifications is given in Schilling's Journal, 1871, page 684.

**122. The combustible** is paraffine which has been highly purified. To fulfil the specifications, it should have a melting point of 55° Centigrade. The paraffine of commerce is a mixture of a number of members of the paraffine series whose chemical constitution corresponds to the general formula, $C_nH_{2n+2}$.

The properties of the successive members of this series are so similar that it is difficult to obtain the substance called paraffine wax having an invariable composition. By an admixture of paraffine oil, vaseline, and paraffine wax in varying proportions, it is possible to maintain the melting point of the mixture at a determinate temperature, while the chemical character of the mixture may show wide variations.

Paraffine wax* being a mixture of indeterminate composition, is for this reason alone unsuited to serve as the combustible in a standard of illuminating power.

**123. The wick** essentially resembles in its character that used in the English candle (page 116), with the exception of its size, as indicated on page 121; and it received from the Commission the most careful attention in all details relating to the quality and cleansing of the cotton, the size and weaving tension of the strands, and even the tension of the wick in the mould.

**124. The colour of the flame and the normal flame height.**— The flame is slightly whiter than that of the spermaceti candle, but it is liable to smoke and to split into a number of points near the top.

The German paraffine candle is supposed to emit unit light strength when burning with a clean wick and a flame height of 50 millimetres. The quantity of combustible consumed an hour is not found to be significant, and is not prescribed in the definition of the standard candle.

* For a discussion of the manufacture of paraffine, and its physical properties, consult "Petroleum," by Boverton Redwood, 1894; especially Vol. I, page 214.

**125.** **The behaviour** of the paraffine candle is generally similar to that of the spermaceti candle, and all the conclusions established for the latter are equally applicable to both varieties of these light standards.

Manufactured under the conditions described, the candles of the German Commission have reached a high state of perfection as a product, but owing to inherent objections to the use of any form of candle for a standard of illuminating power, the use of the paraffine candle has been largely abandoned in Germany and elsewhere.

In addition to the English candle and the Vereinskerze, there are a number of less widely used standard candles, amongst which are the Star and Munich candles. These differ in no essential matters from the forms already discussed.

## THE CARCEL LAMP

**126.** The central draft type of burner, known as the argand, and burning vegetable or mineral oil, furnishes a source of light, not only of remarkable steadiness of flame, but owing to the introduction of the air within the flame, of marked whiteness of colour, compared with similar flames burning in the ordinary manner. The argand type, having been greatly improved in 1802 by Carcel,* subsequently attained great favour in France as a light standard. Its properties were carefully investigated by Audoin and Bévard, working under the supervision of Dumas and Regnault.† Through the labours of these investigators its constants and dimensions were defined. ‡

The carcel lamp, until quite recently, has been the light standard generally recognized and used in France, where the illuminating power of light sources has invariably been

* By the improvement added to the argand lamp by Carcel and Careau, the oil was supplied to the wick at a uniform rate by a pump operated by clock-work. Nicholson's Journal, II, 1802, page 108.

† Annales de Chimie et de Physique, (3) tome lxv, page 423.

‡ Ref. cit., page 489.

expressed in terms of the carcel unit. Though frequently investigated in other countries,* it has not been favourably received, and it probably should not be classed as an international light standard.

**127. The essential dimensions of the lamp,** as defined by Dumas and Regnault for the Paris Gas Association, are given below and illustrated in the sectional drawing of the burner and chimney shown in Figure 37.

| | | |
|---|---|---|
| Greater diameter of the wick tube . . . | 23.5 | millimetres |
| Internal diameter of the air duct . . . | 17 | " |
| Height of the glass chimney . . . . | 290 | " |
| Internal diameter of the chimney at top . . | 34 | " |
| Internal diameter of the chimney at base . . | 47 | " |
| Mean thickness of the glass . . . . | 2 | " |
| Height of the chimney to the bend . . . | 61 | " |

The dimensions of the metallic parts of this standard may be reproduced with sufficient accuracy, but those relating to the glass chimney, the mean thickness of the wall, and the position and curvature of the bend, are from the character of the manufacture of the envelope, not capable of sufficiently exact reproduction.

**128. The combustible** generally employed in the lamp has been colza-oil (rape-seed oil). Such a vegetable oil is not a sufficiently simple and definite chemical compound to satisfy the requirements for the combustible for a light standard. It varies considerably, according to the processes followed in its preparation, and is not obtained in a state of definite purity. Attempts have been made to burn kerosene in the carcel lamp, but no more constant results were obtained.

Dumas and Regnault found, with a consumption of 42 grammes of colza-oil an hour, that they obtained the least

* Consult a paper by Thomas N. Kirkham on Tests of Candles and the Carcel Lamp, and also the accompanying discussion. Proceedings Institute of Civil Engineers; 23, 1869, page 447.

variation of illuminating power for a given variation in the weight of the combustible consumed. Accordingly the carcel lamp is supposed to furnish standard illuminating power when the oil consumption is 42 grammes an hour, the lamp being operated on a suitable balance for indicating the rate at which the oil is burned.

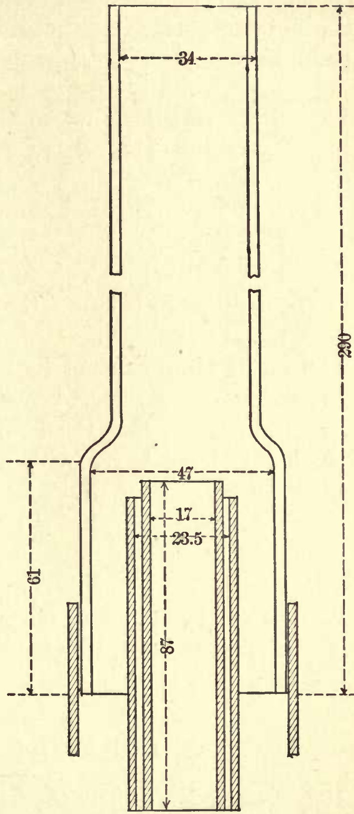

FIG. 37.

**129. The wick** is a matter of considerable importance in such a lamp, the illuminating power varying to a marked degree according as a fine, medium, or coarse wick is used.* The standard wick is one of medium mesh, and consists of 75 threads, and weighs 3.6 grammes a decimetre length. It is essential that perfectly dry wicks be used, and they are commonly kept in a case containing an absorbent of moisture.

**130. The flame height** is not specified for this standard, for its unit working flame is determined only by the weight of combustible consumed, the dimensions of the chimney, and the height of the wick above the tube.

**131. A glass chimney** of the ordinary argand shape encloses the flame. The thickness of the glass is specified at two milli-

* Audoin and Bévard; ref. cit.

metres, but this is a condition which obviously can not be met with precision in the manufacture of glass chimneys. A chimney, in any case, introduces uncertain conditions — the thickness and absorption of the glass, and the reflection of light from its inner surface, are not capable of standard and unvarying definition.

132. **Other variations** are due to the charring of the wick; this being rapidly progressive owing to its free height above the wick tube. When the lamp is lighted, the flame increases to a maximum illuminating power, and then decreases with the charring of the wick.

Another condition difficult to meet is the maintenance of a prescribed distance between the top of the wick and the constriction in the chimney.

The carcel lamp can not be looked upon as a reproducible light standard. Krüss,* investigating it as late as 1894, stated the opinion that the lamp is little better than candles. Though this lamp burns with a greater uniformity of flame than a candle, and the light strength remains fairly constant during a measurement, yet the wick alone causes a variation in the intensity of the light amounting to ± 10 per cent in some extreme cases.

In view of the numerous mechanical sources of variation in this standard of light, it is scarcely necessary to consider the added influences of humidity and atmospheric pressure.

## THE METHVEN SCREEN

133. **Description.** — The Methven standard, in its later form, consists of an argand gas lamp provided with a light-reducing screen (Fig. 38). The burner is a plain, argand one of the Sugg pattern, and is surmounted by a straight, cylindrical glass chimney, two inches in diameter and six inches in height. To the base of the lamp, a flat or concentric plate or screen is

* Schilling's Journal, 1894, page 614.

attached, extending upward beyond the top of the chimney, and placed 1.5 inches distant from the axis of the flame. An opening is left in this screen opposite the centre of the flame; and this is covered with a thin slide containing two rectangular openings, whose longer axes are placed vertically. Each of these apertures is of standard dimensions, adjusted to pass a light flux of two English candles' intensity, with a flame height of three inches for the smaller one and 2.5 inches for the larger. The slide is bevelled to a sharp edge at the openings; a condition required in all light diaphragms. In order that the area of the standard aperture shall not change by corrosion, it is cut in a sheet of silver. All the metallic parts of the standard are given a dull black finish.

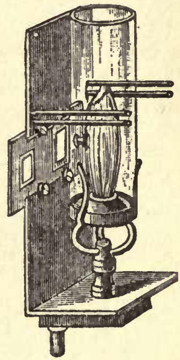

Fig. 38.

Two apertures are usually provided in the same slide: the one for plain gas, and the other for carburetted. The first aperture is 0.233 inch wide and one inch long; and the second one is 0.31 inch wide and 0.585 inch long. The height of the flame is adjusted by means of sight pins projecting on either side of the chimney from the larger screen.

**134. Historical.**—It was announced to the British Association of Gas Managers, in 1878, by John Methven,* that, when gas was burned in similar argand burners, at a given flame height, there was a region to be found in such flames which would radiate the same amount of light for unit of area, or have equal intrinsic brightness of flame (page 31), whatever the quality of gas might be, provided the combustion was complete. He had mapped the flame length by means of a transverse slit of one-quarter inch width, cut in a concentric metal chimney or screen. The position of this slit was adjustable vertically that it might be placed opposite any desired portion of the flame. Methven's

* Journal for Gas Lighting (London); 32, 1878, page 95.

data indicated that the area just below the flame centre gave practically uniform light emission for different qualities of gas, provided the flame height was three inches, the combustion complete, and the light power of the entire flame was between fifteen and thirty-five candles. Possessed of this knowledge of gas flames, he proceeded to adjust the dimensions of the slit so that its value as a light standard should be two English candles. This convention has been uniformly adopted in the manufacture of Methven screens. The extreme simplicity of this device and the steadiness of the light source so commended this standard, that its use became general both in England and in the United States. In this country especially it has been widely employed by incandescent lamp factories as the working standard for the photometry of their product. It has proven especially useful in such cases because of the constancy of the flame, enabling a great number of lamp comparisons to be made in a short time.

It was soon found that Methven had been mistaken in his conclusions regarding the unvarying nature of the standard, and that flames of the same dimensions from different qualities of gas, and varying widely in the quantity of light emitted, contained no areas of invariably constant intrinsic brightness.

**135. The Report of the London Board of Trade in 1881.** — A committee of this organization, after testing the screen, reported* that they found the Methven screen sensibly constant only for the limited flame variation of two candles for any given quality of gas. This result was to have been anticipated. They also found that the quality of the gas burned was of the greatest significance and induced large variations in the value of the light standard. The committee concluded that the Methven-screen standard was not sufficiently constant and reproducible to serve as a standard of light.

A number of equally disparaging reports were made by competent authorities about the same time, and Methven, too,

* Journal of Gas Lighting (London), Oct. 25, 1881, page 720.

seems to have concluded, from subsequent tests, that he had been mistaken in the supposed principle he had announced, and had in reality added nothing to photometry but a certain style of screen, and that this screen, in combination with an argand gas flame, did not constitute a light standard. Apparently, in order to support the apparatus he had devised, he looked about for a new principle with which to endow it.

**136. Carburetting the gas.** — Eventually, Methven was led to experiments in enriching the gas supplied to the burner by means of a volatile hydrocarbon. In particular, gasoline seems to have yielded the best results.

The illuminating power of coal gas is largely due to the hydrocarbons it contains; and if a gas, low in its hydrocarbon content, is led through a suitable reservoir containing gasoline, for example, it becomes enriched to a corresponding extent. On the other hand, a gas of high illuminating power, under similar conditions, absorbs but little hydrocarbon in passing through the carburetor. All qualities of gas when passed slowly through a carburetor containing gasoline are enriched to such an extent that they attain approximately equal illuminating power. These facts were known to Methven at the time, and it remained for him to test their accuracy. He was thus led to make a second announcement, with even more assurance than accompanied the first, that his researches "prove incontestably that in bringing gases of extreme range of quality in contact with the vapour of light petroleum, the illuminating power of such gases is equalized, and that all gases consumed in the same burner, when carburetted, yield the same illuminating power of flame." *

Undoubtedly the Methven screen used with carburetted gas is superior in results to its employment with plain gas; yet this combination by no means meets the requirements for a photometrical light standard, in that the combustible is too complex and uncertain in composition. The use of a glass

* Journal of Gas Lighting (London); 40, 1882, page 42.

envelope for the flame is almost fatal to the employment of such apparatus for a light standard.

In 1885, W. J. Dibdin* on behalf of the London Metropolitan Board of Works, made elaborate tests upon the Methven screen, using plain and carburetted gas. His conclusions were especially unfavourable. A committee of the British Association in 1888 indorsed the conclusions of Dibdin.† The later report of the Dutch Commissioners was even less favourable.‡

Methven subsequently subjected his proposed standard to closer scrutiny and studied the influence upon it of temperature and atmospheric pressure and humidity, and the conditions under which the carburetting could be carried out to best advantage. His work led to no improvements, but rather to abandonment of the screen and argand burner in favour of an open flame jet photometer.§

**137. The errors due to the use of a screen.** — Rawson ‖ called attention to the application of the law of inverse squares in the distribution of light from a standard through a small opening in a screen placed near the flame. He found the illumination of the photometer screen became disproportionately great as the screen was moved toward the Methven slit. He concluded that the sides of the argand flame were the source of the errors, and that in consequence the law of inverse squares could not be rigidly applied — as in the case of open flames.

When the photometer screen is placed some distance from the slit, as at $MN$ in Figure 39, the light-emitting area $mn$ of the flame may be regarded as a sensibly flat surface. Moving the screen along the bar to $PQ$, the illuminating area of the flame is laterally extended to $pq$. It is evident that the

* Journal of Gas Lighting, 45, 1885, page 718; and 50, 1887, page 290.

† British Association Report, 1888, page 39.

‡ Journal of Gas Lighting, 64, 1894, page 1161; serial.

§ London Gas World, Nov. 30, 1889, page 597; also consult Rawson Electrician (London), Oct. 15, 1886, page 479.

‖ Electrician (London), Oct. 15, 1886, page 480.

illuminating power of the edges of the flame at $pq$ is greater than at the limits $mn$ of the former setting. At $PQ$, then, the screen receives a disproportionately greater illumination. This error could be allowed for, by platting a curve of screen illumination applicable to all screen distances that are found desirable. A better suggestion is, that the distance between the Methven standard and the photometer screen be maintained at a fixed value, and that the compared light be moved for accomplishing the equalization.

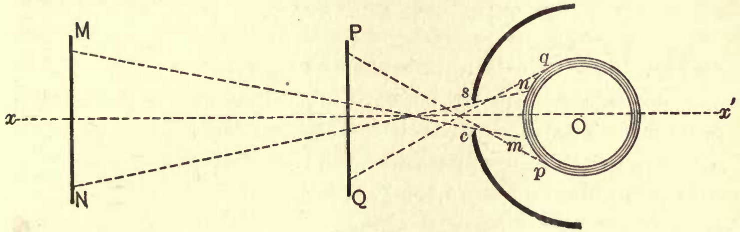


FIG. 39.

The radiant centre of the Methven standard is located neither at the central axis of the flame, nor in the plane of the slit, but changes for each position of the photometer screen.

If the distance from the standard to the screen is great, and the area of the screen is small, then the law of inverse squares may be applied for small changes of the distance, measurements being made in such cases from the surface of the photometer screen to the edge of the slit.

**138. Very small apertures** in a screen for a standard light simplifies the case just considered. If the light source is a plane surface (see page 162) and the aperture is very small, the law of inverse squares applies with sufficient accuracy, and the radiant centre may be taken in the plane of the aperture.

**139. Reflection caused by a glass chimney.** — That portion of the chimney back of the flame will act as a concave cylindrical reflector, and the radiant centre of the reflected light will lie

back of the reflecting surface. The light falling on the photometrical screen will consist of light directly radiated, the uncertainty of whose centre of radiation has already been discussed; and in addition, the screen will be illuminated by reflected light from the inner walls of the chimney with a radiant centre lying back of the chimney. This added complication emphasizes the adoption of a fixed distance between the standard and the photometrical screen.*

## THE PENTANE STANDARD

**140.** This title is applicable to two distinct types of light standards that are to be carefully distinguished from one another. The distinction becomes apparent in the historical development of the apparatus from the earlier *air-gas standard* to the simpler and more compact *pentane lamps.*

**141. The air-gas pentane standard.** — The original memoir on the standard was presented by Harcourt to the British Association in 1877.† After detailing tests made on spermaceti candles and calling attention to their unsatisfactory performance, he describes the development and operation of the standard which has subsequently borne the name of the Harcourt pentane standard.

The first consideration was a combustible which could be readily procured, and be uniform in quality and of a simple chemical nature. For this standard combustible he employed a light distillate from American petroleum, which, after repeated distillation, finally boiled off at 50° Cent. He found the liquid to consist almost entirely of pentane, though it con-

* See paper by B. F. Thomas, Proceedings International Electrical Congress, 1893, page 198.

† "On a New Unit of Light for Photometry," by A. Vernon Harcourt, in abstract in Proceedings British Association, 1877, page 51; and printed at length in the Chemical News, 36, 1877, page 103; also in the Journal for Gas Lighting (London), 30, 1877, page 337.

tained small amounts of other paraffines closely approaching it in chemical composition. This liquid had a specific gravity between .6298 and .6300, and by analysis he found it to contain 83.3 per cent of carbon and 16.7 per cent of hydrogen. Being exceedingly volatile, he determined to use the combustible in the form of a vapour. By calculation and test the proper proportion of air for the complete combustion of the vapour was determined to be 20 volumes of air to 7 volumes of pentane vapour at 60° Fahr., and 760 millimetres atmospheric pressure. In order to prepare the air-gas the requisite volume of air, corrected for humidity and atmospheric pressure, was admitted to a gas-holder over water, and the liquid pentane was then added; this almost immediately vaporized and rapidly diffused into the contained air, and in a short time the mixture of air and vapour was completed and ready for use. He further found that gaseous paraffines are sparingly soluble in water, a property which rendered pentane eminently suitable for such purposes.

The behaviour of pentane vapour under these conditions has been fully verified by subsequent investigators, who have found the water of the gas-holder becoming saturated in a short time with pentane vapour; the air-gas then passes through the gas-holder unchanged in proportions.

**142. The burner.** — The air-gas was burned in an apparatus of very simple construction. The burner consisted essentially of a brass tube one inch in diameter and four inches in length. This tube was capped by a brass disk one-half inch thick, and perforated centrally by an opening one-quarter of an inch in diameter, such a large opening being adopted to lessen the mechanical error in the reproduction of the burner. The air-gas was not forced through this opening under especial pressure, but was allowed to diffuse into the air assisted and regulated by its own gravity, or controlled by a sensitive pressure regulator.

Under the conditions of preparation, and at the pressure and temperature already noted, this pentane air mixture behaves as

a perfect gas; a fact which is necessarily fundamental for such a standard as the one described.

The open flame thus obtained was very steady, and the light was especially white in colour. At a temperature of 60° Fahr. and at normal atmospheric pressure, the flame maintained a practically constant height of $2\frac{5}{16}$ inches, burning the air-gas at the rate of 0.5 cubic foot per hour. The dimensions of the apparatus were adjusted to yield a light strength equal to that of the spermaceti candle, burning 120 grains of combustible the hour.

**143. Tests of the air-gas standard.** — In order to assign a proper value to the various reports on the pentane standard, favourable and unfavourable, which will be noted in the discussion, it is necessary to note that the science of photometrical light standards has made rapid advancement toward precision of requirements, especially within the last decade. There has been within this period a decided gain in accuracy of investigation, and the sources of variation in the operation of light standards have been subjected to closer scrutiny and measurement. Though these various reports doubtless represented opinions justifiable at the time of their publication, they are no longer to be accepted as conclusive. Their chief value at present concerns the logical development of the pentane standard. These observations apply similarly to the discussion of each of the more important standards of illuminating power.

A committee appointed by the London Board of Trade* to test the reliability of the various light standards, after studying the behaviour of candles, the keats lamp, the Methven screen, and the Harcourt air-gas flame, came to the conclusion that the three first named were too faulty to serve as photometrical standards of illuminating power; they further declared the Harcourt pentane standard to be satisfactory and sufficiently constant in operation and reproduction. In a series of nineteen measure-

* Journal of Gas Lighting (London), 38, 1881, page 719.

ments made by two operators working independently, the greatest difference between the values found was 1.8 per cent. They recommended the employment of the Harcourt air-gas standard to the exclusion of the others named.

In 1883 Harcourt described certain improvements in the standard.* Instead of mixing the gas in the proportion of three volumes of air with 1.05 volumes of vapour in preparation for the test, he introduced liquid pentane into a gas chamber from a suitable reservoir, through a device which enabled the operator to control the rate at which the pentane was supplied. The proportion, then, in which the pentane vapour and the air mixed was entirely under control. Harcourt had found that the height of the flame furnished a precise indication of the proportion of the air-gas mixture. By these improvements, instead of mixing the gases in a definite volume ratio, the operator adjusted the flow of pentane vapour until a flame height of 2.5 inches was reached; the particular height denoted the correct proportion of air and pentane vapour; or, in general, under the conditions of burning the gas, the flame height was a function of the proportion in which the two gases were mixed. Still later, additional improvements of a somewhat similar character were made.†

The improved Harcourt standard received an emphatic endorsement by a committee on light standards of the British Association.‡ In 1888 they presented a report which was based on a considerable number of tests, but their investigations seem to have been somewhat deficient in thoroughness. In detail, the report stated that "the pentane standard of Mr. Vernon Harcourt is reliable and convenient, and fulfils all the conditions required in the adoption of a standard of light. This standard attains this end by its having no wick, and consuming a material of definite chemical composition. The experiments of your committee absolutely show that the light

* Proceedings British Association, 1883, page 426.

† Journal of Gas Lighting (London), 49, 1887, page 900.

‡ Proceedings British Association, 1888, page 41.

was not altered when the specific gravity of the pentane was .632 or .628 instead of the specified value of .630."

Prior to the report of the committee of the British Association, W. J. Dibdin * on behalf of the Metropolitan Board of Works had made a series of painstaking measurements on standard candles, the carcel and keats lamps, and the Harcourt air-gas standard. In the latter case he investigated the purity of commercial pentane, and the influence of its impurities on the illuminating power of the standard. These comparative tests resulted favourably for the pentane standard, and its exclusive adoption was strongly recommended.

The comparison standard which Dibdin employed was a gas flame supplied from a large storage tank, on the supposition that the stored gas would yield a constant illuminating power for a given flame height, day after day.† He found, however, that gas stored over clear water deteriorated greatly; in one case it amounted to lowering the illuminating power from sixteen to ten units. It was further noted that after a certain interval the deterioration ceased and the gas then remained fairly constant, though changes in the temperature of the stored gas would cause variations in the illuminating power of the flame.

From the difficulties inherent in the maintenance of a standard comparison light, it is apparent that results obtained from day to day would not be accurately comparable.

An extension of these tests was subsequently made and included a study of the pentane lamp as distinguished from the pentane air-gas standard. In this later form the standard is simple, practical, and easily manipulated.‡ The scientific value of Dibdin's investigations may be judged from the fact that they were endorsed in the report of the British Association. §

* Journal of Gas Lighting, 45, page 673; serial.

† Dibdin, ref. cit., page 577.

‡ Journal of Gas Lighting, 50, page 290. Compare summary on page 143.

§ British Association Report, ref. cit.

## THE PENTANE LAMP

**144**. The air-gas standard, even in its improved form, was strictly a laboratory apparatus, and not suitable for general use. A successful attempt was subsequently made to develop it into a practical standard by Harcourt and W. S. Rawson.* In this form, known as the Woodhouse and Rawson pentane lamp, it is essentially a spirit lamp.

**145**. **The wick** extends within two or three inches of the point of ignition, and has less significance in this lamp than in any other light standard. So long as it is clean and introduces no foreign matter into the combustible, and preserves a sufficiently rapid capillary flow of the pentane, it has no influence whatever on the light value of the flame, being too far beneath it to char when the lamp is burning.

**146**. **The production of the flame.** — The pentane delivered by the wick is vaporized by the heat of the wick tube, and the vapour ignites at its upper end. The outer casing, which is constricted at this point to a diameter of 20 millimetres, serves as a chimney and screen as well, for the base of the flame. The lower part of the upper metal chimney is similarly constricted to a diameter of 20 millimetres, the two chimneys being separated to a distance adjusted by an appropriate gauge. The end of the flame is sharply pointed, and is visible through the regulating slits in the chimney. This arrangement of chimneys constitutes a modified Methven screen, the opening between them being so placed that the light is emitted from the central portion of the flame.

**147**. **The influence of the heating effects** in the operation of this lamp is especially significant. The wick tube is air-jacketed throughout its length by a closed outer concentric tube in order that the wick tube may eventually attain a constant tempera-

* Journal of Gas Lighting (London), 51, page 371. British Association Report, 1887, page 617.

ture. This is sufficiently high to vaporize the highly volatile pentane at a point some three inches below the ignition point of the flame. The third or outer cylinder acts as a draft chamber, and passing the air over the jacketed wick tube, supplies it to the flame, heated to some extent. The result of this arrangement is that the temperature of the flame is increased very considerably above that of an open pentane flame burning freely.

These features — the heated air supplied to the flame, and the intense heating of the end of the wick tube — are prime sources of the variations in light strength and the unreliability of the pentane lamp.

**148. Description of the ten-candle pentane lamp.** — It has been seen that Harcourt first used a mixture of air and pentane vapour for the combustible, and later devised a lamp in which liquid pentane was burned with a wick. Finally he has proposed a reversion to the air-gas type.

Formerly pentane lamps gave a light intensity of one or two candles; but a greater intensity is very desirable. To obtain a steady and compact flame having a luminous intensity of ten candles, Harcourt* found it necessary to adopt the principle of the argand burner. The use of a glass chimney caused such variations in the intensity of the light that it was finally dispensed with, and an open flame impinging into a metal chimney was adopted. This later lamp differs from the liquid-burning lamp chiefly in the substitution of the argand principle for the simple jet flame. The ten-candle lamp was adopted by the Metropolitan Gas Referees of London as the official standard of illuminating power, and in consequence of this official sanction it merits description at length.

The ten-candle lamp (Fig. 40) employs air saturated with pentane vapour; and the air-gas so formed descends by its gravity to a steatite ring burner. The top of the flame is hidden from view by a long brass chimney *A*, above the steatite

* Gas World (London), 28, 1898, page 951.

burner *B*, while a mica window in the brass tube enables the height of the flame to be gauged and adjusted. The chimney is surrounded by a larger tube *D* in which the air is warmed by the chimney, and so tends to rise, making a current which, descending through another tube *E*, supplies air to the centre of the flame. No glass chimney is required and no other means need be employed to drive the air-gas through the tubes.

The saturater *S* is connected with the burner by means of brass tubing, though in the first lamps a rubber tube was employed. In the lower end of the connecting tube is placed a small cock. This should always be opened for a minute or two before lighting the lamp, so that any condensation of pentane which may have gathered in the tubing may be drawn off. The small micrometer cock next to the base of the burner should be kept closed during this operation. When the lamp is in use, both cocks on the saturater box should be wide open and the height of the flame be regulated by the micrometer cock. The saturater is, at starting, about two-thirds filled with pentane, and it should be replenished from time to time

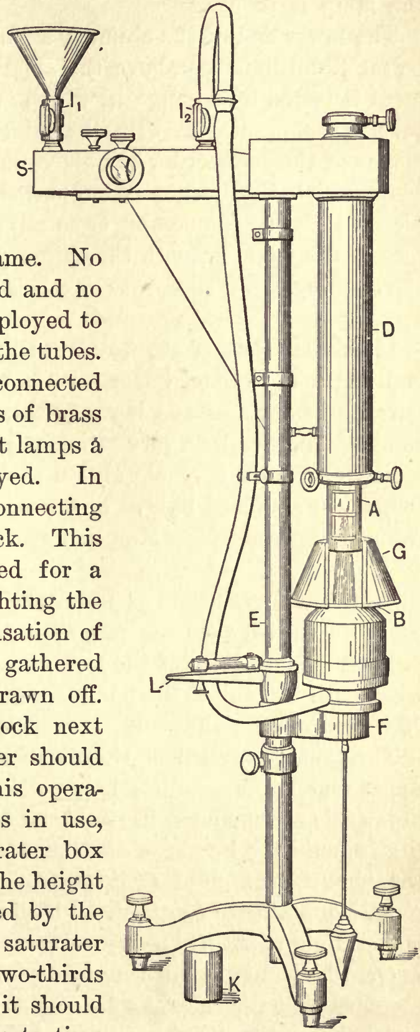


FIG. 40.

so that the pentane is always visible through the glass window. The stopcock *I* for admitting air should be fully open when the lamp is in use.

The lower end of the chimney should, when the lamp is cold, be set 47 millimetres above the steatite ring, and this adjustment is tested by a gauge *K*, which is provided. The exterior tube *D* communicates with the interior of the burner ring by means of the connecting box above the tube *E* and the bracket *F* on which the burner is supported. A conical shade *G* is placed about the flame and is so adjusted that the whole surface of the flame beneath the chimney *A* may be seen through the opening.

**149. The colour of the flame.** — Pentane vapour, being especially rich in carbon, burns with a brilliant white flame, and burning in the pentane lamp at a heightened temperature of combustion, it emits a very satisfactory quality of light, and one which conforms very closely to the requirements for a photometrical standard light. This property especially commends the pentane lamp for a standard of illuminating power.

**150. The flame height of the Woodhouse and Rawson lamp.** — The interval between the chimneys being adjusted by a standard gauge, the height of the flame is regulated by adjusting the wick until the tip of the flame appears vertically at the centre of the regulating slit.

The central portion of the flame is the source of light, the upper and lower portions being screened by the metal chimneys; this arrangement having been adopted on the supposition that, should the height of the flame vary within certain limits, the quantity of light emitted from the central zone would remain practically constant. In this sense the pentane lamp is a development from the supposed discovery of Methven, upon which he based the design of his screen. Methven assumed that the central zone of a gas flame of definite height emitted a constant light strength independently of the quality

of the gas burned. In contrast, Harcourt assumed that in the use of a combustible of constant quality, the central zone emitted a constant light strength for varying heights of the flame. According to Harcourt's tests, this assumption was experimentally verified. It is now known that this assumption is not correct, and that Harcourt's experiments were either lacking in sensibility, or were in error from lack of constancy in the comparison light, for Liebenthal, investigating this matter with especial care, has found that the light strength varies considerably with the flame height. For flame heights adjusted either to the top or bottom of the slit, or at intermediate points of $\frac{1}{3}$, $\frac{1}{2}$, and $\frac{2}{3}$ of its length, the light strengths were in the proportion of 97.9, 99.5, 100, 99.5, 97.9.* These data indicate that the proper adjustment of the flame height is at the centre of the slit, and that the flame should be constantly maintained at this height. In comparison with the open and unscreened flames of the candle and the amyl acetate lamp, with their large alteration of illuminating power for a change of one millimetre in flame height, the change in the light strength of the pentane lamp of about 0.4 per cent for each millimetre alteration of height is very small, and in this respect the pentane lamp exhibits the advantage of screening a flame and confining the radiation of light to the central zone of the flame.

151. **The radiant centre** for the light does not lie in the axis of the flame. Harcourt† ascertained experimentally that the law of inverse squares could not be applied to this screened flame by taking the radiant centre on the axis, or in front of the flame; but for distances from it not less than ten inches, no sensible error resulted from taking the luminous centre midway between the axis and the outer tube. This was subsequently confirmed by Liebenthal,‡ who found that, taking the illumina-

* Electrotech. Zeitschrift, 1895, page 657.

† Journal for Gas Lighting (London), 51, page 371.

‡ Liebenthal, ref. cit.

tion of a unit area of the photometrical screen when at unit distance from the radiant centre, at $L$ units, the illumination $J$, when the screen was placed at a distance $r$ from the flame axis, was

$$J = \frac{L}{\left(r - \frac{\rho}{2}\right)^2}, \tag{64}$$

in which $\rho$ is the radius of the constricted portion of the chimney about the flame, and $L$, $r$, and $\rho$ are expressed in terms of a common unit of length.

**152. The influence of moisture and atmospheric pressure.** — The same investigator pursued a lengthy series of tests to measure the influence of the humidity of the air and the atmospheric pressure on the illuminating power of the pentane lamp. The comparison standard in these tests was an incandescent lamp, a fact which makes these results comparable, and imparts to them an authority not inherent in the work of earlier investigators. The effect of humidity is expressed by

$$y = 1.232 - 0.0068\,x.^* \tag{65}$$

The light strength $y$ is stated in terms of the amyl acetate standard, and $x$ denotes the litres of moisture in the cubic metre of dry air free from carbon dioxide. The variation in light strength caused by humidity is so large that it becomes a marked objection to the use of such a light standard. However, the correction factor is so definitely stated, that it suffices to use a satisfactory hygrometer such as an Assmann, at the time of making the test. The equation is graphically expressed in Figure 41.

The variations in light strength consequent on changes of atmospheric pressure are, definitely stated,

$$\Delta y = 0.00049\,(b - 760), \tag{66}$$

* Compare this formula with that for amyl acetate flames, page 155.

where $b$ is the reading of the barometer in millimetres. The corrections, both for humidity and atmospheric pressure changes, are so significant that no value can be attached to photometrical measurements with the pentane lamp, which have not been accompanied by observations of the barometer and hygrometer.

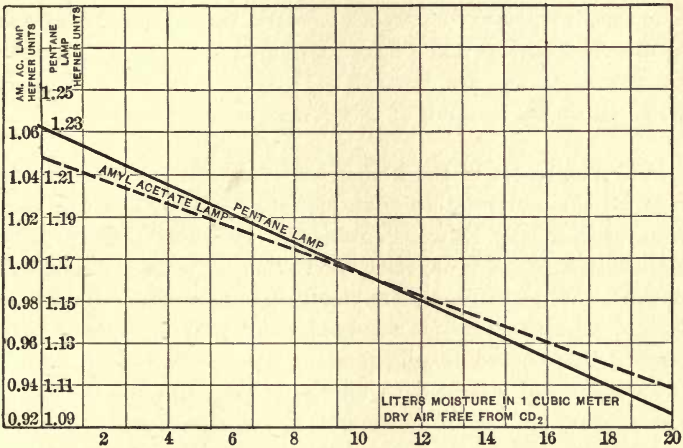


FIG. 41.

**153. The pentane lamp** possesses undoubted value as a light standard in certain respects pointed out in this discussion. It has two marked disadvantages, which cause it to yield precedence to the amyl acetate standard, — (1) Pentane is one of a series of paraffines whose properties are so similar that it is exceedingly difficult to obtain it free from admixture with other members of the series, and consequently the combustible for the pentane lamp is not obtainable as a definite and invariable chemical substance; (2) In the operation of the lamp the temperature of the vaporizing and screening tubes continually increases until a thermal equilibrium is reached. While this is going on, the flame gradually lengthens, and must be lowered by depressing the wick. No measurements should be made with the lamp

until the flame height becomes constant, which ordinarily requires about thirty minutes.*

The temperature effect is not confined alone to altering the flame height, but the intrinsic brightness of the flame is increased as well, as this is a function of the temperature for any given combustible. It is these things especially which render the pentane lamp ultimately unsuited for a standard of illuminating power. These strictures should not be applied peculiarly to the pentane flame, but they are applicable to all gas flames which are burned in envelopes under conditions which cause the heating of the burner and the envelope.

**154. The report of the Netherlands Commission.** — One of the most recent and reliable examinations of light standards has been made by the Dutch Commission on photometry.† They reported a decided preference for the mechanical arrangements of the pentane lamp, but advised certain modifications in its design, and the use of a mixed combustible. After many experiments they determined upon the proportions by weight of nine parts of benzol with one hundred parts of ethyl ether. The specific gravity of the standard solution should be 0.7335 at 15° Cent.; of the benzol, 0.8860; and the ethyl ether 0.7215. They reported having found that slight impurities in the constituents did not affect the light value of the standard.

This solution did not burn differentially, as might be supposed, from its behaviour in fractional distillation, but was consumed uniformly, and the specific gravity of the combined liquid in the lamp was that of the original solution. This modified standard of the Netherlands Commission can not be regarded as an improvement over the pentane lamp. There appears no satisfactory reason to justify the report other than the desire to introduce a novel or peculiar standard.

* Liebenthal, ref. cit.

† Journal of Gas Lighting (London), 1894, page 1161; also Schilling's Journal, 1894, page 613.

## THE AMYL ACETATE LAMP

**155.** This type of lamp, frequently termed the Hefner-Alteneck,* or simply the Hefner lamp, is by far the most noteworthy of all the existing light standards. As will be developed in the course of this discussion, this standard has been subjected to accurate and thorough investigation, and its faults as well as its merits are clearly understood. The worst feature of the amyl acetate lamp is, perhaps, the colour of the flame, and no other photometrical light departs so far from the physiological requirements of the ideal standard. Its wide currency is due wholly to its constancy and ease of reproduction. The German Commission † states that the Hefner lamp deserves to be given the preference for excellence over the pentane lamp, a statement whose significance is apparent in view of the action of the Electrical Congress of 1893. ‡

**156. The Reichsanstalt amyl acetate lamp.** — The Hefner lamp was modified in its details to conform in the design and the dimensions of its parts to the results obtained from extended investigations at the Physikalische Reichsanstalt. This form, commonly known as the Reichsanstalt lamp, has been universally adopted as the standard one for the use of amyl acetate.

The lamp is shown in section in Figure 42. The material used in its construction is brass, with the exception of the wick tube, *C*, which is of German silver to avoid corrosion by the combustible; and for a similar reason the walls and parts in the interior of the lamp should be thoroughly plated.

The wick is moved by a worm gear, *ef*, which actuates two spur wheels, $w$ and $w_1$. All the fittings of the lamp are attached to the cap *B*, which unscrews from the cup *A*, for filling. The cap marked *D*, is removed when the lamp is in use, and at other times it should be kept screwed over the wick tube.

* For the first announcement of this light unit see a paper by F. von Hefner-Alteneck, Elektrotech. Zeitschrift, 1884, page 20.

† Elektrotech. Zeitschrift, Oct. 10, 1895, page 655.

‡ Proceedings International Electrical Congress, 1893, page 18.

The dimensions stated in the figure are in millimetres, and certain of them must be followed with great accuracy. This

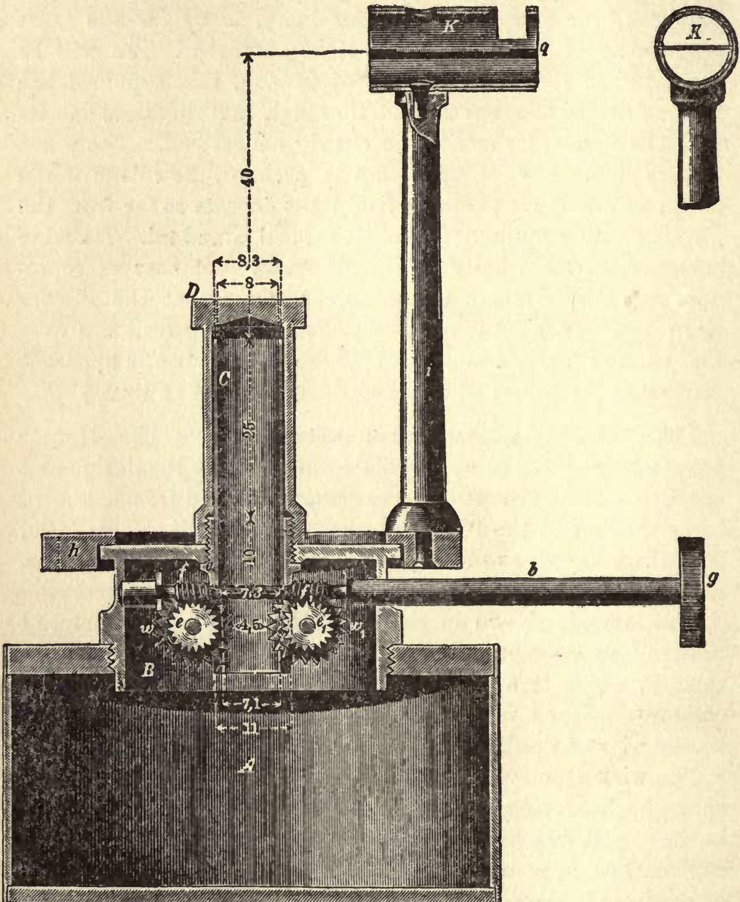


Fig. 42.

is especially the case with the diameter and the thickness of the wall of the wick tube, and the flame height of 40 millimetres.

A plate, *h*, moves in adjustment, concentrically with the wick tube, and carries a pillar topped with the Krüss optical flame gauge, shown in end elevation at *K* in the figure, and in side elevation in Figure 43. The essentials of the flame gauge are a magnifying lens and a screen of ground glass fastened in

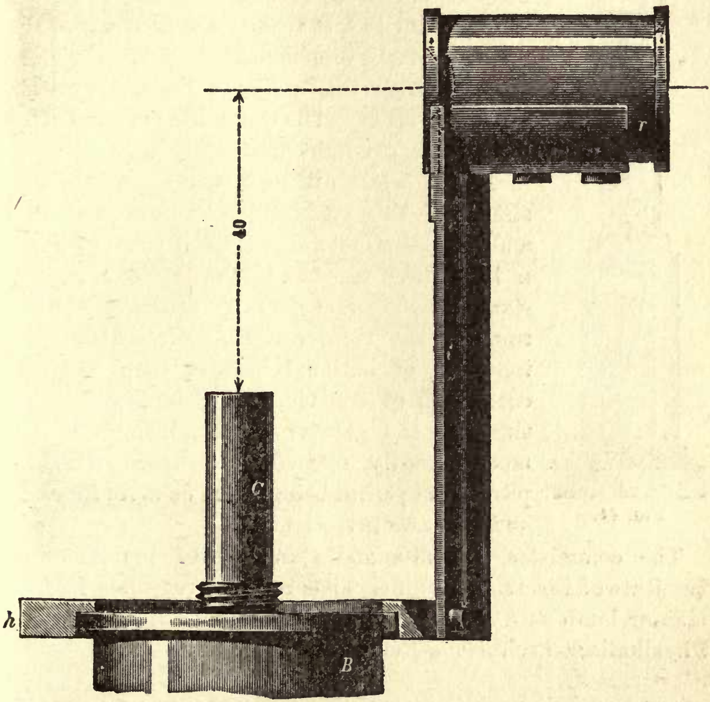


FIG. 43.

the eye piece. The glass screen has a diametrically horizontal scratch on it, cutting the optical axis of the gauge.

The test gauge, Figure 44, is provided for the verification of the flame height distance from the top of the wick tube to the axis of the flame gauge. It is placed over the wick tube, and when the top of this tube is viewed horizontally through the

slits in it, there should be, for correct adjustment of the height, the slightest observable clearance. The top of the gauge is ground off to a slight bevel, giving a truly horizontal edge, which, viewed through the flame gauge, must sharply coincide with the scratch on the glass screen. This most ingenious arrangement of gauges enables the operator to test readily the accuracy of this very important dimension.

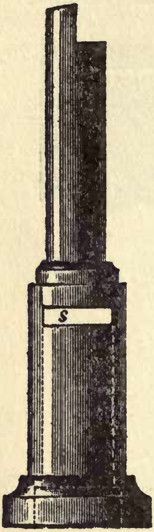

FIG. 44.

In England this standard light met with a tardy reception. The Committee of the British Association on light standards, in their report in 1888,* while calling attention to the constancy of this standard, both in reproduction and operation, regarded it as distinctly inferior in both these respects to the Harcourt pentane standard. They especially criticised the red tinge of the Hefner light. Disregarding the influence of national bias in each case, the conclusion of the German Commission is entitled to the greater weight, being not only more recently formed, and hence with improved lamps, but being based on more thorough and accurate investigation.

The committee on units and standards of the American Institute of Electrical Engineers has recently recommended the Hefner lamp as a standard, provided it is certificated by the Physikalisch-Technische Reichsanstalt.†

**157. The amyl acetate.** — The combustible being the essential feature in the production of any photometrical standard flame, it is readily seen that the Hefner lamp derives its excellence from the chemical simplicity and definite composition of the substance which it burns. Amyl acetate is a colourless liquid having the chemical constitution $C_5H_{11}C_2H_3O_2$, and burns

* British Association Reports, 1888, page 40.

† Transactions American Institute Electrical Engineers, 1897, page 90.

with a clear flame, rather feebly luminous and somewhat reddish in colour. It is prepared commercially from the distillation of amyl alcohol obtained from fusel oil, with a mixture of acetic and sulphuric acids; or, by distilling a mixture of ethyl alcohol, sulphuric acid, and potassium acetate. It is extensively used in the arts as a solvent for certain colloids and resins, this liquid being yellow in colour and quite impure, and entirely unsuited for use in the Hefner lamp.

**158. The purity of the amyl acetate.** — For photometrical purposes the amyl acetate should be purchased from reliable dealers. The German Gas and Water Association has, with characteristic care in such matters, assumed to furnish amyl acetate of suitable purity.*

When secured from other sources the chemically pure variety should be specified, and before using it certain tests of its purity are to be applied. The tests for amyl acetate prescribed by the Physikalisch-Technische Reichsanstalt are: †

*First*, the specific gravity at 15° Cent. should be from 0.872 to 0.876.

*Second*, when distilled in a glass retort at least ninety per cent should pass over between the temperature limits of 137° and 143° Cent.

*Third*, the reaction should be practically neutral, and blue litmus paper not be sensibly reddened by it.

*Fourth*, it should mix, bulk for bulk, with ether, benzine, or carbon bisulphide, without becoming milky.

*Fifth*, a clear solution should result upon shaking in a test-tube, 1 c.c. amyl acetate with 10 c.c. ethyl alcohol, ninety per cent Tralles, and 10 c.c. of water.

*Sixth*, a drop placed on white filter or blotting paper should evaporate without leaving a greasy spot.

The amyl acetate should be kept in a glass-stoppered bottle

* This is to be obtained from Dr. Bunte, Karlsruhe.

† Zeitschrift für Instrumentenkunde, 13, page 257; also Schilling's Journal, 1893, page 341.

and preferably be stored in a dark place, as it has a tendency to decompose in strong light.

Thus specified, the amyl acetate is sufficiently pure to meet the requirement of uniformity in the composition of the combustible, and to this extent the Hefner lamp is a light standard which can be satisfactorily reproduced. The foreign substances liable to be found in amyl acetate are water, amylic and ethylic alcohols, but none of these in the proportion liable to occur in the chemically pure acetate of commerce has a sensible effect on the illuminating power, according to tests by Hefner-Alteneck.*

**159. The wick.** — The character of the wick appears to be practically without influence on the illuminating power of the lamp, provided it does not fill the tube tightly; for, owing to the low vaporization temperature of the amyl acetate, the wick does not usually project into the flame. As a rule, the wick supplied by the maker of the lamp is a woven one, though a number of strands of candle wick, slightly twisted together, gives satisfactory results. Loosely woven round wicks for spirit lamps are entirely satisfactory. Should the notched wheels of the regulation Hefner lamp be employed to move the wick in the tube, a woven wick will be preferable, as it will not catch in their teeth. In any case the wick should be washed in distilled water, then soaked for a time in a one or two per cent solution of concentrated ammonia, and finally thoroughly washed in distilled water.

In the prescribed model of the Hefner lamp the feeding wheels are actuated through a worm-gearing; if this is carefully made with broad wearing surfaces it is satisfactory, but in many lamps the workmanship is poor, and in consequence the gear train is a frequent source of annoyance. The amyl acetate, too, especially if it is slightly acid, in time may so damage the wearing surfaces that the train will not work. Both the design of the gear train, as well as its position within

* Journal of Gas Lighting (London), 59, 1892, page 295.

the bowl of the lamp, are open to criticism, and the arrangement should be improved by the makers.

It has been frequently stated that the wick does not char, but this is in part misleading. The top of the wick does char when the lamp has been burned a short time, but the rate of charring is so low it does not materially affect the illuminating power during a short period of burning. Each time the lamp is used the wick should be evenly trimmed, removing all loose ends and charred portions.

**160. The wick tube and test gauge.** — The Physikalisch-Technische Reichsanstalt's specifications require that the thickness of the wick tube shall not be more than 0.02 millimetre larger, or 0.01 millimeter smaller than the normal thickness (Fig. 42), and that the free length shall not differ more than 0.5 millimetre, nor the inner radius more than 0.1 millimetre from normal dimensions. The length and diameter of the wick tube, and the thickness of its walls, are essential from the influence of the heating of the tube on the light value of the flame.

A test gauge should be furnished with each lamp in order to standardize the flame height. When the gauge is properly fitted on the top of the lamp, and the end of the wick tube is viewed horizontally, a mere clearance space, not exceeding 0.1 millimetre, should be visible between its edge and the bottom of the slot in the gauge. This test requires great care to avoid an error of parallax. Then, looking at the optical gauge, the upper edge of the test gauge should sharply coincide throughout its entire length with the line scratched on the ground glass plate. Since the variation of one millimetre from the normal flame height of 40 millimetres will cause the illuminating power to vary by nearly three per cent, it is evident that the conditions above outlined will require careful investigation.

Bearing in mind that the Hefner lamp burns with an open flame, and granting that the standard was satisfactory in all other respects, the disproportionately great influence which the flame height and the dimensions of the wick tube exert, would

make it a questionable standard, except in thoroughly practised and skilful hands.

**161. The colour of the flame.** — The amyl acetate flame burns with a markedly red tinge. According to the criterion established in Chapter I, both the green and blue colour groups are too feebly represented for it to be even approximately a standard of normal illumination. This is a very serious disadvantage and gives rise to uncertainty and error when comparing it photometrically with a whiter light. In this respect the amyl acetate flame is markedly more deficient than even the spermaceti candle flame.

**162. The flame height.** — This is prescribed at 40 millimetres above the edge of the wick tube, and this particular value has been selected with reference to the most constant behaviour of the flame. If the light intensity of the flame corresponding to a height of 40 millimetres is taken as unity, then the intensities corresponding to the flame height in general between 20 and 60 millimetres have been found by Liebenthal* to be:

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Flame heights, | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 60 | millimetres |
| Intensities, | 0.38 | 0.55 | 0.70 | 0.85 | 1.00 | 1.12 | 1.25 | 1.50 | units |

These results established that the light intensity for flame heights above 40 millimetres varies as a linear function of the flame height amounting to 2.5 per cent for each millimetre change in height; for heights less than 40 millimetres there was similarly a linear function found, in this case amounting to three per cent for each millimetre change in height.

If the symbol $J$ be taken to denote the intensity at a flame height, $h$, and $L$, the intensity for the normal flame height of 40 millimetres, the following equations express these linear functions; for flame heights between 40 and 60 millimetres the relation is:

$$J = L\,[1 + 0.025\,(h - 40)] \quad . \quad . \quad . \quad . \quad (67)$$

and for flame heights between 20 and 40 millimetres:

$$J = L\,[1 - 0.030\,(40 - h)] \quad . \quad . \quad . \quad . \quad . \quad (68)$$

* Elektrotech. Zeitschrift, 1888, page 97.

The tip of the amyl acetate flame is sharply pointed, and through its feeble luminosity and red colour, it becomes very difficult to locate with exactness the point at which the luminous flame ceases. Nor would this point be located at the same place by all observers, owing to the differing degrees of sensitiveness of eyes to light. Even though the optical flame gauge does magnify the image of the flame-tip, there is a large personal equation and limit of uncertainty in adjusting the flame height.

**163. Reproducibility.** — In this respect the Hefner lamp far excels all standards which have come into general use. Upon summarizing the preceding discussion, it is found: that the combustible is chemically simple and definite; the wick is without influence on the light value so long as it is clean and is not compressed to the extent that it fails to feed sufficient combustible to keep the end of the wick constantly wetted. Other details are merely those of mechanical construction, which, owing to the exactness required in many of the dimensions, should be of the very best character.

The Reichsanstalt will not certificate a lamp whose illuminating power deviates by more than two per cent from its standard lamp. This limit of error of two per cent is apt to be misleading, since no Hefner lamp can be relied upon within this limit by all observers. Owing to the added influence of sources of variation yet to be discussed, the probable working limit of reliability is seldom less than five per cent. However unsatisfactory such conditions may be, it must be admitted that the Hefner lamp is far less unreliable than any other light standard.

**164. The influence of temperature.** — The Hefner lamp in burning is subject to two sources of temperature effects. Its own heat of combustion will produce expansion of the wick tube and other parts, but variations from such sources are rendered negligible by the thinness of the walls of the tube leading to rapid radiation. The second temperature variation, that

of the atmosphere surrounding the flame, seems to exert no discernible influence on the illuminating power of the flame.

**165. Influence of atmospheric moisture.** — The extent to which the percentage of moisture in the air enveloping the amyl acetate flame affects its light value demands most careful attention on account of the magnitude of the errors introduced. A series of accurate tests has been made by Liebenthal extending over a sufficient length of time to enable him to express the value of the influence of atmospheric moisture.* The annexed table states the average value for each month in the year, but in any one month the fluctuations may be as great as the widest difference among the average monthly values. This would be liable to occur not only in certain months of the year, but would probably change from year to year. In short, for reliable measurements, it is necessary to determine the humidity of the air surrounding the flame and introduce a corresponding correction for the value: —

Observed Monthly Averages for Light Value of Hefner Lamp. (Fig. 45.)

| | Mean Moisture for the Month in Litres, per Cubic Metre | Corresponding Mean Light Value |
|---|---|---|
| January, 1895 | 6.11 | 1.016 |
| February " | 5.25 | 1.019 |
| March " | 6.77 | 1.01 |
| April " | 9.14 | 0.999 |
| May " | 10.29 | 0.994 |
| June " | 12.31 | 0.979 |
| July " | 14.43 | 0.970 |
| August " | 13.35 | 0.972 |
| September " | 11.07 | 9.986 |
| October " | 10.44 | 0.991 |
| November " | 8.87 | 1.000 |
| December " | 7.18 | 1.009 |

* Elektrotech. Zeitschrift, Oct. 10, 1895, page 655.

The greatest variation shown by this table was between 101.9 per cent and 97.0 per cent, or a change of 4.9 per cent in the illuminating power. The tests, however, were extended over practically two years, with a maximum difference noted between 103.3 per cent and 94.8 per cent, or a change of 8.5 per cent. The conclusion at which Liebenthal arrived was that so far as

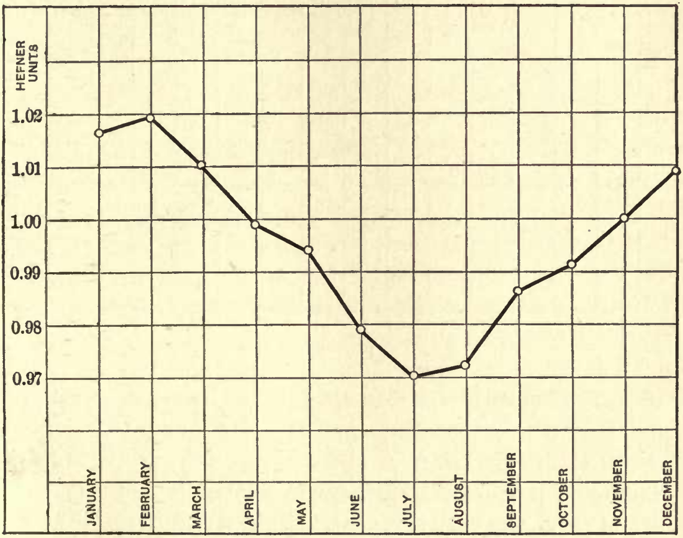


FIG. 45.

atmospheric moisture is concerned, the light strength of the Hefner lamp can be relied upon within a mean limit of the normal light strength of $\pm$ 4 per cent. The equation connecting these results is for humidity between three and eighteen litres per cubic metre,

$$y = 1.049 - 0.0055\,x \quad . \quad . \quad . \quad . \quad . \quad . \qquad (69)$$

$y$ being the illuminating power of the Hefner lamp at a humidity of $x$ litres of moisture to the cubic metre of air free from carbon dioxide. These same relations are exhibited graphically in Figure 46. From the equation it is seen that when $x$ is

8.8, a unit light value is indicated. The significance of this particular value for the humidity will be pointed out later on.

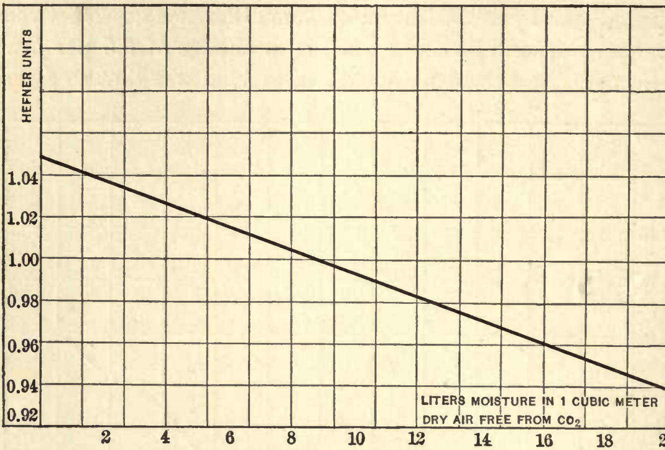


FIG. 46.

**166. The influence of carbon dioxide.** — The same investigator found that between carbon dioxide contents of 0.62 and 0.93 litres to the cubic metre of the air, the light strength varied through 0.2 per cent. With good ventilation of the photometrical room, the variations in the light strength of the Hefner lamp due to the carbon dioxide content of the air should be negligible.

For expressing the quantitative relations between the content of carbon dioxide and the illuminating power there exists the equation

$$y = 1.012 - 0.0072\, x_1 \quad . \quad . \quad . \quad . \quad . \quad (70)$$

in which $x_1$ states the litres of carbon dioxide to the cubic metre of dry air. The equation further shows that the unit value for the Hefner light is taken for a content of carbon dioxide of nearly 1.7 litres per cubic metre.

As photometrical rooms are often small and usually poorly ventilated, the moisture and carbon dioxide arising from the

flames under test, and the breath of the experimenters as well, are probably responsible for a considerable share of the errors and uncertainties to which ordinary photometrical measurements are liable.

**167. The influence of atmospheric pressure.**—Within the limits of ordinary variations of atmospheric pressure, Liebenthal's investigations * established the expression,

$$\Delta y = 0.00011\,(b-760) \quad . \quad . \quad . \quad . \quad . \quad (71)$$

$\Delta y$ being the change in illuminating power of the amyl acetate flame based on unit value of $y$ for the normal atmospheric pressure of 760 millimetres. So far as the influence of barometric pressure alone is concerned, the reading of the barometer $b$ expressed in millimetres, in the above equation, will, by its solution, enable an accurate correction to be made for tests at all ordinary atmospheric pressures other than normal. Accordingly a fall of the barometer of 25 millimetres or about one inch, would decrease the luminosity of the flame only about 0.28 per cent.

This is another addition to the complexities of photometry with open flames, and emphasizes the desirability of a standard free from such disturbing influences.

In view of the number and value of the influences modifying the light strength of the accepted standards, it is little to be wondered at that the photometrical results of careful and reliable observers should be so wide of agreement. Criticism should not be made against either the knowledge or ability of such observers, nor the resources of scientific measurement, but rather there is necessitated on the part of the general scientific public a broader knowledge of the obscurities and difficulties of the subject, and also how well-nigh hopeless is the attempt to equate physical phenomena against psychological events.

* Liebenthal, ref. cit.

**168. The value of the Hefner unit.** — Naturally upon the advent of the Hefner lamp, and the recognition of its importance, it was felt to be desirable to express its illuminating power in terms of candles or carcels. This amounted to an attempt to express definite ratios between several uncertainties and another only somewhat less uncertain. In consequence, there have been published practically as many values for the ratios as there were observers who had attempted the investigation.

The candle power of the Hefner lamp is a value which does not admit of determinate expression. In accordance with a custom in such cases a ratio will be presently stated, but granting its accuracy, the ratio only obtains for the particular experiments from which it was deduced.

**169. On the substitution of the term "Hefner unit" or its equivalent for candle power.** — If the candle is an unsuitable light standard, not only for scientifically exact but even approximate photometrical measurements, the term "candle power" has no definite meaning, and its use is questionable as the name for the unit of the illuminating power (refer to page 34). A change would doubtless be made without hesitation were a thoroughly scientific and generally accepted standard of light available. The term "candle power" would perhaps give place to the name of the approved unit, based on the standard adopted. But the term "candle power" being meaningless as a quantitative expression, and the Hefner unit being fairly concise, it might be advisable to follow the example of foreign photometricians and evaluate illuminating power in Hefner units* or its equivalent.

**170. The significance of the Reichsanstalt certificate.** — Practically every phase in the construction and operation of the amyl acetate lamp has been made the subject of thorough

* Report stating agreed-upon names, symbols, and dimensions for photometrical units. Schilling's Journal, 1897, page 548.

investigation on the part of the German Gas Commission and the Physikalisch-Technische Reichsanstalt. In this manner the best dimensions have been determined for the various essential parts of the lamp, and the best conditions established under which to operate it. Guided by this thorough knowledge the Reichsanstalt has constructed a normal or standard lamp with which other lamps offered for test are compared. Certificates are issued by the Reichsanstalt upon comparing lamps, provided their structural dimensions are within limits already referred to, and the illuminating power does not differ from that of the standard lamp more than two per cent.*

The certificate means that such a lamp will reproduce the Hefner lamp unit within two per cent under normal atmospheric pressure, and with average humidity, taken to be 8.8 litres of moisture to the cubic metre of dry air and normal average carbon dioxide content, provided that satisfactorily pure amyl acetate is burned, and the lamp is properly operated.†

**171. General directions.** — In order to prepare the lamp for use, insert the wick into the wick tube and test the adjusting wheel train, which must move the wick easily and smoothly without catching in its threads, or sticking. Then the top of the wick should be trimmed off straight and smooth with the top of the tube, using sharp scissors and avoiding irregularity of surface or stray thread ends.

The top of the lamp is unscrewed and the amyl acetate is poured into the lamp until it is nearly filled, leaving sufficient space that the addition of the wick will not cause the lamp to overflow. The top of the lamp is then screwed into place, and after the wick has become thoroughly wet, the lamp is lighted, the flame adjusted to normal height, and the lamp is placed permanently in position on the photometer bench. According

* For further details consult Zeitschrift für Instrumentenkunde, 13, 1893, page 257; also Schilling's Journal, 1893, page 341.

† *Ibid.*

to earlier directions, the lamp should burn freely for at least ten minutes before making measurements of its illuminating power, but wider experience with the lamp has shown that it is better to extend this time to twenty, or even thirty, minutes, when the flame will certainly have attained constant luminosity. The lamp once placed should not again be disturbed.

On the top plate near the wick tube a few small vent holes will be found, and these must be inspected and kept open. The temperature of the photometer room is preferably regulated between 15° and 20° Centigrade.

The lamp is not to be used in a close or small room, to avoid excess of moisture and carbon dioxide, unless rapid ventilation can be had without creating drafts in the room.

Immediately upon completing the measurements the lamp should be emptied and cleaned, for through the decomposition of the amyl acetate the metal parts are liable to corrosion; the wick should also be removed, and the lamp and wick tube well rinsed with ordinary alcohol. It is preferable that the wick be thoroughly washed in clean alcohol and then dried and stored for further use. A convenient place for keeping the wick is a tightly stoppered test tube.

It is not advisable to use the amyl acetate emptied out of the lamp, a second time. A little experience will enable the filling of the lamp to be proportioned to the length of the tests so that little need be wasted. So long as the end of the wick rests in the amyl acetate, the supply is sufficient for the flame.

## PROPOSED STANDARDS OF ILLUMINATING POWER — OR; THE ARC STANDARD OF LIGHT

**172.** In the operation of the continuous current arc lamp a crater forms on the positive carbon which becomes the seat of high incandescence of the materials of the pencil, and is the source of the greater portion of the light radiated from the arc. A flame of feeble luminosity compared with the lumi-

nous power of the positive crater extends to the tip of the negative pencil, which has a much lower temperature than the carbon at the positive end of the arc. The constitution of this arc flame, as well as its illuminating power, have been subjects of controversy and wide difference of opinion.

The flame has been regarded, by some, to be composed of very minute and highly incandescent particles of carbon, projected from the positive to the negative carbon. According to another opinion, the carbon of the positive crater passes through its true boiling point and, vaporizing, forms the arc flame.

The temperature at which this occurs under normal atmospheric pressure has been approximately determined to be 3500° Cent.* The consensus of experimental evidence has satisfactorily established the occurrence of true ebullition in the electric arc. The boiling point of carbon at approximately 3500° Cent. is thus a physical constant of the same significance as the boiling point of water or the melting point of an iron; but it partakes of the complexities of the melting point of an iron rather than the simplicity of the boiling point of water. These complexities originate from the several allotropic forms in which carbon may occur and from the influence of the hardness of the carbon pencil.

It is assumed, but not yet completely demonstrated, that all forms of carbon when raised to the temperature of ebullition, exist in the atomic grouping which is characteristic of graphitic carbon. On the latter assumption, all forms of carbon will boil at the same definite temperature, which will vary only in proportion to the atmospheric pressure.

It was discovered by Abney in 1878 † that the intrinsic brightness (page 31) of the positive crater of a given carbon

* Violle, Proceedings International Electrical Congress, 1893, page 262; also Abney and Festing, Proceedings Royal Society, Vol. 35, 1883, page 331.

† Abney, Proceedings Royal Society, 1878, pages 157 and 161; also British Association Report, 1883, page 422.

was constant and independent of the watts absorbed in the arc. He also found constancy in the whiteness, or colour grouping of the radiations from the positive crater.

In 1892 it was independently proposed by James Swinburne and S. P. Thompson* to adopt the light radiated from a unit area of the positive crater of the electric arc from pure carbons, as a unit of standard light.

Violle,† investigating the same subject, found that the intrinsic brightness of the positive carbon is rigorously independent of the power expended in producing the arc between such wide limits as 500 and 34,000 watts. He also examined the arc with a spectrophotometer and noted that the brightness of any particular colour group or wave length is equally independent of the power absorbed in the arc.

Blondel endeavoured to realize a working arc standard.‡ He protected an arc from air currents in a suitable box and placed before it a water-cooled screen at a distance of 2–3 centimetres from the crater. This screen was pierced with an opening before which rotated a diaphragm. In such a case it suffices to multiply the area of the opening in the diaphragm with the intrinsic brightness (page 31) to obtain the value of the standard in use. The value found by this investigator for the intrinsic brightness § varied between 150 and 163 candles, ‖ (Star) though Trotter ¶ found a value of 70 candles (English) for hard carbons.

In use, the distance from the light standard to the screen is measured (page 131) from the diaphragm.

Blondel also investigated the influence of the carbons on the

* Proceedings International Electrical Congress, 1893, page 267; also Philosophical Magazine, Vol. 36, 1893, page 124.

† Reference cited, page 259.

‡ Proceedings International Electrical Congress, 1893, page 315.

§ Reference cited, page 332.

‖ Violle states the Star candle has an illuminating power equal to 1.15 English candles.

¶ Proceedings International Electrical Congress, 1893, page 315.

intrinsic brightness of the crater.* As was to be supposed, he noted considerable variations. For carbons of great purity and uniform character he found an agreement of results within two per cent. The values obtained with soft carbons and cored carbons were widely different from those obtained when hard carbons were burned. He found cored carbons from their lack of uniform brightness of crater were unsuitable for such standard work. On the other hand, a cored carbon was desirable to maintain the crater in a fixed position.

The quality of the carbon — its hardness or softness, amongst other things † — affects both the quality and quantity of light emitted by the arc with a given absorption of power; the light diminishing in quantity and becoming bluer with increasing hardness of the carbons. The entire subject of the influence of the character of the carbon on the quantity and quality of light radiated from the arc merits more complete investigation than it has hitherto received.

The suggestions to employ an arc standard of light have not yet materialized in a practical form. The essential question involved is similar to that of all flame light standards, — the invariable character of the material supplying the flame. With the possibility of producing carbon of known uniformity of character the difficulties involved in the introduction of such a standard would be removed. Standards of this nature would be desirable for the invariable quality of the light emitted, provided the carbons were dependable, and for the added reason that it so nearly corresponds with the physiological requirements of the eye. The arc standard of light is an inviting subject for further investigation, and it is to be hoped that renewed efforts will be made to obtain reliably uniform quality of carbons.

* Reference cited, page 329.

† W. M. Stine, Electrical World, New York, Feb. 23, 1895, page 223; April 6, 1895, page 420; also Electrical Engineer, New York, Oct. 3, 1894, page 268, and Electrical Review, London, Oct. 19, 1894, page 460.

## PROPOSED STANDARDS OF ILLUMINATING POWER

### INCANDESCENT PLATINUM STANDARDS

**173.** The previously discussed standards have depended for their emission of light principally upon the incandescence of carbon released within the flame envelope from chemical combinations. The incandescent carbon was found to be associated with other light-emitting substances such as luminous gases, while the temperature at which the incandescence of the flame constituents occurred was modified by influences whose specific value could not be determined. The attempt to simplify the character of the light standard by avoiding the indefinite modifying influences and employing a suitable and simple substance for the incandescent source of light led to the development of the platinum, or so-called *absolute* standards.

**174. The term "absolute standard"** employed in this connection must not be taken to imply the relations which it expresses when used to designate a class of very precise measurements. In its latter use it refers to such cases in which the quantitative relations of a phenomenon may be expressed in terms of constants and the dimensions of length, time, and mass. Applied to the platinum standard it implies that the light strength may be specified by reference to a set of conditions which are completely known and capable of exact definition. This use of the term "absolute" is a questionable one, and may prove misleading, for were the standard realized it would be impossible to express the value of the light strength in terms of the dimensions involved, the light strength being ultimately a physiological and not a physical quantity.

**175. The Violle standard.** — The immediate development of the incandescent platinum standard proceeded from the inves-

tigations of Violle.* The selection of the metal was guided by the considerations that the molten metal should not oxidize, and could be obtained in a sufficiently pure state. Silver and platinum were especially investigated, and the latter was finally selected.

A vigorous effort was made to secure official sanction for the Violle standard from the International Electrical Congress at Paris, in 1881. In the final action on the subject the Congress retained the carcel lamp as the working standard of illuminating power, pending the action of an international jury which it recommended should be appointed to pass finally on proposed electrical units, and determine their precise definitions.† Such a jury was appointed, and a renewed investigation of the proposed incandescent platinum standard was made in coöperation with them.

Although the investigation of the subject was yet in its initial stage, and had not been generally attempted, and the photometrical adaptability of incandescent platinum was by no means established, the jury, assembling for final action on April 28, 1884, in a conference on Electrical Units, adopted the hypothetical platinum standard, legally defining it thus, "The unit of each simple light is the normal quantity of light of the same kind emitted in the normal direction by a square centimetre of the surface of molten platinum at the temperature of solidification. The practical unit of white light is the quantity of light emitted normally by the same source." ‡

The spectrophotometrical relations to a standard were thus defined, and the unit for illuminating power, and the standard of normal white light.

* Annales de Chimie et de Physique, (6) III, page 73. Platinum rendered incandescent by an electrical current was studied photometrically by Zöllner; Poggendorff's Annalen, 100, 1857, page 381; and 109, 1860, page 256.

† Congres International des Électriciens, 1881, pages 331–359.

‡ Electrical Review (London), May 10, 1884, page 401; also La Lumière Électrique, 12, 1884, page 270.

The Violle standard, in its earlier form especially, was an expensive apparatus, requiring about a kilogramme of platinum.* A large amount of auxiliary apparatus, too, was required in its operation, and, in consequence, the investigation of the standard has not been general.

The platinum was melted in a specially formed lime crucible, by means of a compound blowpipe burning oxygen and illuminating gas. After the fusion of the metal, the crucible was moved under a water-jacketed screen, pierced with a circular opening, whose area was one square centimetre. The light emitted from the molten metal was reflected by a mirror to the photometrical screen, and balanced against a carcel comparison lamp. Advantage was taken of the fact that a molten metal lowers in temperature until the stage of solidification begins, when the temperature remains constant until the process is completed. Platinum, too, in common with iron recalesces brightly during solidification. Violle showed, by following the cooling with a thermopile,† that the temperature remained practically constant for a considerable time during solidification.

As the metal reached the point of solidification, or the flashing point, the light strength increased markedly, and the photometrical screen required rapid adjustment to obtain a balance while this condition lasted. This setting alone was significant, and upon it the value of the standard was based. Usually but one measurement could be made in the duration of the flashing, and it was necessary to fuse the platinum anew each time a measurement was desired. This proposed standard proved not only tedious to operate, but required great experience and a high degree of skill to obtain results of any value. Violle states ‡ that the quality of light from the molten platinum is richer in violet rays than the light from the carcel lamp.

* Measures Électriques, Eric Gerard, page 53.

† Violle, ref. cit.

‡ *Ibid.*

**176. Modifications of the Violle standard** were attempted to simplify the apparatus and decrease its cost. Siemens's modification appears to have found some favour. He employed a narrow strip of platinum foil and heated it to fusion by an electrical current.* The significant measurement of the light in this case was made just at the moment of fusion. As this occurs suddenly, and the radiating surface is destroyed by the rupture of the foil, the measurement of the light strength had to be made very quickly. As the platinum approached the melting point the photometrical screen was kept continually in balance, until the light failed, when the last setting was taken for calculating the standard light strength.

The fusion of the platinum does not occur at such a uniform temperature as does the solidification. The temperature of fusion has been found to vary depending upon the past history of the metal. The mechanical effects of rolling out the foil and bending it, and repeated heating short of fusion and cooling, may cause the fusion temperature to vary considerably, and in consequence, the strength of the light emitted.

Though the Siemens apparatus is less expensive and more easily operated than that used by Violle, the sources of error are so numerous, and the errors may attain such magnitude, that it has been abandoned.

**177. The Reichsanstalt investigations** conducted by Lummer and Kurlbaum have been the most thorough and reliable to which the platinum standard has been subjected.† They found that the slightest impurity in the platinum caused sensible variations in the light strength. In the course of these investigations the character of the impurities found in platinum was determined, and satisfactory methods were found to render it sufficiently pure.‡

* Elektrotech. Zeitschrift, 1884, page 245.

† *Ibid.*, 1894, page 474.

‡ Mylius and Förster, Zeitschrift für Instrumentenkunde, 1892, page 93.

Eventually it was considered advisable to abandon the definition of the light standard by the points of fusion or solidification of the platinum. They succeeded in obtaining a definition by reference to a fixed temperature short of fusion. Their apparatus was so complicated and required such skill for its manipulation that the process was considered unsuited for the definition of the standard of light.

The report to the British Association* in 1888 on light standards, already alluded to, stated that "Professor Violle's standard of molten platinum is not a practical standard of light." Later investigations have so abundantly confirmed this decision that the proposed platinum standard is no longer considered a feasible one.

**178. On the contradictory character of photometrical data.**—The literature of photometry is singularly conspicuous for discrepancies and contradictory numerical data. Methven's supposed discovery of the constancy of the light strength in the central zone of a gas flame, independent of the quality of the gas within certain limits, and Harcourt's observations on the constancy of the pentane flame through slightly varying heights, were each established by tests apparently as carefully performed as those which have shown these assumptions to be erroneous. Especially when the voluminous data of the values of the illuminating power of candles, lamps, and gas flame standards are compared, the variations are so great that they bring into question the entire subject of the standards of light. Aside from such causes of variation, already noted in the discussion, a very potent one has been the variable character of the light with which these comparisons have been made.

Prior to the present exact knowledge of the amyl acetate and pentane flames, there was no accurately reproducible light strength of a flame to employ for a comparison standard. The comparison lights employed were kerosene, carcel, and keats

* British Association Reports, 1888, pages 40 and 47.

lamps, and jet and argand gas flames. The measurements made at any one time, while they might be comparable amongst themselves, were not so with measurements made at any other time, from the lack of a constant and reproducible standard.

How comparable would measures of extension prove if the unit of length, the foot or metre, required renewal daily, and was not reproducible with accuracy and constancy?

It was not until the incandescent lamp came into use as a secondary standard that measurements made at different times became comparable. Through the constancy of the light strength of the incandescent lamp, observations of the influence of humidity on the light strength of flames, extended through the entire year, became possible. The investigations made since the advent of the incandescent lamp in the capacity of a comparison standard are of more quantitative value than all that preceded them, and their data may be accepted with a confidence which earlier tests did not inspire.

## THE WORKING VALUES OF LIGHT STANDARDS

**179**. This subject has invariably proven confusing to photometricians. The values found in various treatises and periodical contributions have been so wide of agreement that there appeared no grounds for the selection of any particular value for a given light.

The values presented in this paragraph have been chosen for the reasons that they were obtained by extensive experiments carried on probably by the most accurate and scientific methods and apparatus recorded in the literature of photometry; and they are the result of the joint labours of the German Gas Commission and the German Physical Institute. They were selected more especially because the incandescent lamp was used as a comparison standard after its behaviour for such purposes had been carefully studied and its constancy assured. These values are:

| | |
|---|---|
| The Paraffine Candle (Vereinskerze) * at a flame height of 50 millimetres | = 1.2 Hefner Units. |
| The English Candle * at a flame height of 45 millimetres | = 1.14 Hefner Units. |
| The Pentane Lamp † set with one-candle gauge | = 1.17 Hefner Units. |

The Hefner unit noted here is the light strength of the amyl acetate lamp adjusted to the normal flame height of 40 millimetres under the atmospheric pressure of 760 millimetres, and a humidity of 8.8 litres of moisture to the cubic metre of dry air free from carbon dioxide. Stating the light strength in terms of the normal Hefner unit by $L$, and the litres of moisture in the cubic metre of dry air free from carbon dioxide by $x$, the corrected equation of the amyl acetate lamp is,

$$L = 1.049 - 0.0055\,x \ddagger \qquad (72)$$

and similarly for the pentane lamp it is,

$$L = 1.232 - 0.0068\,x. \ddagger \qquad (73)$$

*Reference values.* — The comparative light strength of the French decimal candle ‖ with that given by other recognized standards, has recently been determined by Laporte: ¶

| | Decimal candle | Carcel lamp | Hefner lamp | Paraffine candle |
|---|---|---|---|---|
| Decimal candle . . . . . | 1 | 0.104 | 1.13 | 0.955 |
| Carcel lamp . . . . . . | 9.6 | 1 | 10.9 | 9.2 |
| Hefner lamp . . . . . . | 0.885 | 0.092 | 1 | 0.815 |
| Paraffine candle . . . . . | 1.05 | 0.109 | 1.23 | 1 |

* Schilling's Journal, 1893, page 342; also Zeitschrift für Instrumentenkunde, 1893, page 259.

† Liebenthal, Elektrotech. Zeitschrift, 1895, page 655.

‡ Liebenthal, ref. cit.

‖ The International Electrical Congress at Paris in 1889, gave the name of *bougie décimale* to the twentieth part of the Violle platinum standard.

¶ Bulletin de la Société Internationale des Électriciens, May, 1898, XV, page 181; F. Laporte.

# CHAPTER V

## COMPARISON LIGHTS, OR SECONDARY STANDARDS OF ILLUMINATING POWER

### THE INCANDESCENT LAMP

**180**. This source of illumination is not only the especial object of photometrical practice in electric lighting, but it possesses additional interest from being a proposed light standard; and is, as well, of unusually great value as a comparison light.

In this latter aspect, certain of its physical characteristics demand extended discussion.

**181. The surface of the filament** of the incandescent lamp may range in appearance from rough and dull black, to polished smoothness and a bright gray colour. Whether the filament thread is silk or cellulose, after carbonization, its surface will be somewhat irregular and dull black in colour; this is remedied in the subsequent process of flashing.* As generally applied, the process consists in placing the filament in a jar containing an atmosphere of a volatile hydrocarbon, such as gasoline, at a pressure of about one-quarter of an atmosphere; there the filament is connected in circuit and the voltage is increased slowly until the filament is brought to a white heat. The hydrocarbon vapour in contact with the filament is decomposed and deposits a layer of carbon upon it. The deposited layer of carbon may vary greatly in its character.

* For a discussion of the filament and processes of its preparation, refer to Chap. V, The Incandescent Lamp; G. S. Ram.

The influencing causes are the density of the hydrocarbon atmosphere, and the temperature as well as the rate of deposition. The coating is hard, smooth, and bright gray in colour, when the flashing has taken place in a hydrocarbon atmosphere of low density, and at a high temperature, slowly applied. There are many reasons for considering such a gray coating to be graphitic carbon. The dull black, superficial layer, on the contrary, resembles lampblack in its properties.

**182. The emissivity of a filament** is affected to a marked extent by the character of the superficial layer of carbon. In this connection certain observations made in the first chapter are to be insisted upon: light and heat waves being similar in character, yet differ in frequency, and when the energy of the electrical current heats the lamp filament to incandescence there emanates from it both heat and light radiations. Were it possible to obtain a filament, the nature of whose superficial layer was such that it emitted only light radiations, all the electrical energy expended in the filament would be transformed into light, producing an ideally efficient source of illumination. Again, the carbon filament may be heated to a temperature short of incandescence and the electrical energy supplied be expended in heat radiation. While noting that these are the limiting conditions, if the temperature of the carbon filament be increased until it becomes incandescent, there coexist radiations both of light and heat energy. The emissivity of the filament is affected to a marked extent by the character of the superficial layer: carbon filaments having a dull black surface show a higher rate of emission of both light and heat energy than the bright gray filaments.

Weber* has found an average relation in the emissive power of these varieties of filament surfaces of 100 to 75.5 in favour of the dull black one. He calls attention to the values of the radiating power for lampblack and graphite obtained in

* Physical Review, 1894, page 116.

the classical experiments of Leslie, of 100 to 75. The conclusion then follows that gray filaments are at least coated with a layer of graphitic carbon.

In general, then, the flashing of carbon filaments usually results in a coating of gray, graphitic carbon with lowered emissivity of the filament, having a lessened rate of radiation both for light and heat.

The proportion of light to heat radiation, at a given temperature of incandescence, is practically the same for both the dull black surface, and the gray, graphitic one, though it requires less expenditure of energy to maintain this temperature in the latter filament than in the former one.

For instance,* a filament, which before flashing and at a temperature A, gave an illumination of 21 candles with 84 watts expenditure; when flashed and again operated at the temperature A the relation was 15 candles for 60 watts. By increasing the temperature to a value B, the initial light strength of 21 candles was obtained for 68 watts of energy. Had the filament, before flashing, been operated at the higher temperature B, it would have yielded 28 candles for about 90 watts of energy expended, or, tabulating this: —

| Filaments | | Candles | Watts | Watts per candle |
|---|---|---|---|---|
| Black | at temperature A | 21 | 84 | 4 |
| Gray | at temperature A | 15 | 60 | 4 |
| Black | at temperature B | 28 | 90 | 3.22 |
| Gray | at temperature B | 21 | 68 | 3.24 |

The rate of emission for light radiations from incandescent lamp filaments is at four watts for the candle power, from 100 to 170 candle power for the square inch of radiating surface. This may be increased by raising the temperature to the point

* The Incandescent Lamp; G. S. Ram, page 63.

of rapid disintegration of the filament, to about 1900 candle power for the square inch of emitting surface.*

**183. A change in emissivity due to repeated heating.** — The candle power of an incandescent filament, after a certain epoch in its life has been passed, undergoes a marked and progressive change. There seem to be a number of causes bringing about this result, some of which will be noted later; but the immediate cause is a change in the emissivity for heat and light energy. The influence of prolonged heating increases the emissivity of the surface of the filament, and the change is greatly accelerated by increasing the pressure on the filament above what may be considered its normal voltage, resulting in an increased temperature of incandescence. G. S. Ram † cites an experiment in which a filament had been operated at a constant voltage until the bulb was blackened. He then found the emissivity had increased 23.6 per cent.

**184. The temperature of the filament** with the differing varieties of commercial lamps has been generally estimated to be between 1200° and 1500° Cent. Weber, ‡ by measurements of the total radiation, and taking into account the radiating area of the filament, has been able satisfactorily to determine its temperature. He found the general practice of incandescent lamp illumination to cover a range extending from 1127° to 1327° (1400° to 1600° absolute) Cent. for small lamps; and for larger lamps these values were increased by 50°. The relation between the temperature of the filament and the candle power emitted is shown graphically in Figure 47, which was platted from Weber's data. It is noteworthy that curve $A$ relates to a flashed or gray filament, and curve $B$ to one having a black surface, the emissivity of the black filament being considerably greater than that of the gray one.

* G. S. Ram, ref. cit., page 64. † *Ibid.*, page 199.

‡ Physical Review, 1894, p. 116.

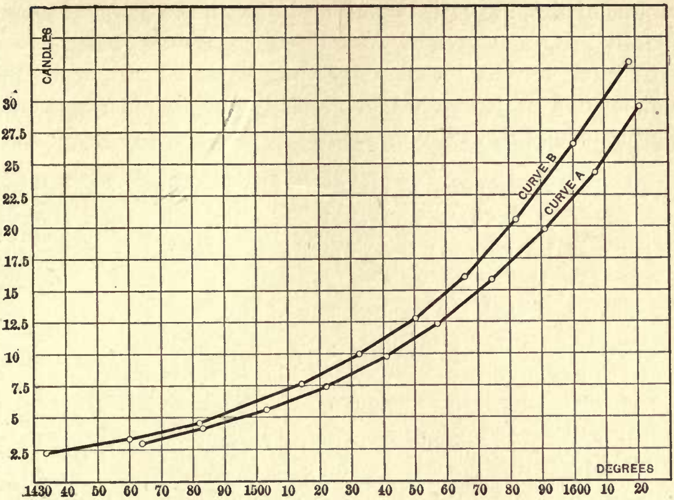


FIG. 47.

**185. The temperature change of resistance** of the carbon filament is a negative one, and does not necessarily have the same value for different filaments. The flashing process increases the value of the temperature coefficient of resistance. The relation between the cold and hot resistance of a lamp is then an uncertain quantity, depending on such conditions as can not be exactly determined.

**186. The hysteresis of the resistance of the filament.** — When the pressure applied to a filament is continuously increased until bright incandescence is obtained, and then continually decreased at the same rate, the resistance corresponding to a given candle power will not be the same in each case, being higher in the first instance, and lower in the second, than a certain intermediate value, which would be obtained by keeping the lamp at the given candle power. Or, in general, for rapid changes in the pressure applied to the filament, its change of resistance lags behind the change in volts. The

amount of this lag varies considerably with the filament tested. Usually after a change in pressure the filament attains a constant value for the resistance within 10 or 20 minutes. The phenomenon of hysteresis is probably due to some molecular readjustment within the filament.

187. **The vaporization of carbon** in the chamber of the incandescent lamp is now generally accepted as experimentally proven. It has already been noted (page 161) that in the case of the arc light the carbon reaches its boiling point and becomes vaporized. Although one of the most permanent substances at ordinary temperatures, carbon, similarly with platinum for example, when rendered highly incandescent, softens and slowly evaporates. Evidences of such action are seen in the blackening of incandescent lamp globes and in the shadows in the carbon film caused by the legs of the filament.* There are reasons for holding that evaporation from the superficial layer of the filament must go on to some extent at all temperatures of incandescence, though it is not until the filament is heated to such a temperature that it softens that the rate of evaporation becomes considerable. At any temperature the rate of evaporation will depend on the character of the superficial layer of the filament, hard, gray filaments losing less than dull black ones. The immediate effect of the lessening of the cross section through evaporation is the increase of its resistance. Weber † states when lamps were operated for 30 hours below a certain critical temperature the resistance remained practically constant. When the critical temperature was exceeded, which in one case occurred at 1330° Cent., the resistance rapidly increased.

Again, the critical temperature was found to vary with different lamps, showing that the temperature of marked volatilization varies with the character of the carbon.

* W. A. Anthony; Transactions American Institute of Electrical Engineers, 1894, page 146; also W. M. Stine, ref. cit., page 181.

† Weber, ref. cit., page 210.

**188. A study of unflashed and flashed filaments.** — Evans * has made a remarkable series of experiments which clearly develop a number of important features in the physics of the incandescent lamp. His best results were obtained from filaments apparently made from parchmentized paper, purchased on the market and not especially made. Though they are of a type no longer in use, their behaviour is in keeping with filaments made from silk and cellulose. As purchased, the filaments were black in colour, with a rough, untreated surface.

They were first properly mounted and the bulbs carefully exhausted, and then subjected to photometrical and electrical measurements. Subsequently, they were removed from their chambers, flashed, remounted, and again tested. Finally, they were a second time dismounted, and were coated with a rough, dull black layer of firmly adherent carbon and similarly tested.

The data of the several tests on one particular filament are:

| Untreated Filament | | | | Filament Flashed in Hydrocarbon Vapour | | | Filament Flashed in Coal Gas | | |
|---|---|---|---|---|---|---|---|---|---|
| Candle power | Volts | Current | Watts | Volts | Current | Watts | Volts | Current | Watts |
| 4 | 45 | .86 | 38.7 | 34 | .95 | 32.7 | 39 | 1.16 | 45.2 |
| 10 | 56 | 1.12 | 62.7 | 39 | 1.12 | 43.7 | 44.5 | 1.38 | 61.4 |
| 20 | 62 | 1.28 | 79.7 | 44 | 1.28 | 56.3 | 49.5 | 1.53 | 75.7 |
| 30 | 66.5 | 1.4 | 93 | 47 | 1.47 | 67.2 | | | |
| 40 | 69 | 1.48 | 102 | 49.5 | 1.54 | 76.2 | | | |
| 50 | 71 | 1.54 | 109 | 52 | 1.67 | 86.8 | | | |
| 60 | 73.5 | 1.62 | 119 | 52.8 | 1.73 | 91.3 | | | |

The flashing process was carried on slowly in an atmosphere of a hydrocarbon of a high boiling point. In this treatment they acquired a smooth, highly polished, and bright gray surface. The subsequent flashing was done in an atmosphere of

* Proceedings of the Royal Society, 40, 1886, page 207.

coal gas, which imparted a dull black, sooty-looking coating, but which adhered very firmly to the filament, and could be handled without rubbing off, and be brought to high incandescence without rapid vaporization.

Between the untreated and the gray-flashed surfaces there was apparent at any given candle power a great gain in efficiency. In a given amount of energy radiated, the proportion of light energy to heat energy emitted was considerably higher with the gray surface. As already indicated, Weber and Ram have shown that in such cases the filament with a gray surface is invariably at a higher temperature of incandescence. The gray surface has a lowered emissivity over the black one, and to produce an illumination equal to that of the black surface the gray-coated filament must be operated at a higher temperature. The gain in efficiency is not, then, due to a more efficient radiation as regards light rays, at a given temperature, but that in consequence of reduced emissivity, the temperature must be raised to produce a given illumination. The gain in flashing, however, is one of stability of surface, which enables the filament to be operated at a higher temperature without producing rapid volatilization of the superficial layers of carbon. A higher temperature of incandescence invariably implies an increased proportion of light energy in the total energy radiated. In this same connection Evans prepared filaments from carbonized fibre. In particular, one was mounted with a black, untreated surface, while a second one was flashed to a bright gray surface. These filaments were otherwise alike in all essential respects and dimensions.

When tested at the *same illuminating power*, the results were:

| | Candle power. | Watts | Watts per candle power |
|---|---|---|---|
| Black filament . . . | 20 | 100 | 5 |
| Gray filament . . . | 20 | 74 | 3.7 |

When tested under conditions of nearly *equal efficiency*, the results were: —

| | Candle power | Watts | Watts per candle power |
|---|---|---|---|
| Black filament . . . | 28 | 113 | 4.04 |
| Gray filament . . . | 17.4 | 71 | 4.08 |

Here, again, for the same illuminating power, — 20 candles, — the gray filament shows a markedly higher efficiency over the black one. When tested at the *same temperature*, or equal watts for unit of light emitted, the superior emissivity of the black filament was clearly shown, for the gray filament exhibited but 62 per cent of the illumination of the black one.

Such results apparently indicate that at a given temperature, black and gray carbon surfaces have the same proportionate emissivity for light and heat rays, though the total emissivity of the black carbon is greatly in excess of that of the gray one.

**189. The light absorption** in the incandescent lamp is a factor which can not be assigned a known influence. The thickness of the glass walls of the chamber may vary not only amongst lamps, but in any one lamp from paperlike thinness to a very considerable thickness. The variations in the character of the glass and in the thickness of the walls must alter the amount of light absorbed by the glass envelope. The absorption of light is still further increased by the film of carbon deposited on the inner walls of the envelope.

**190. The relation between illuminating power and the energy.** — The incandescence of the filament is a function of the energy transformed within it, and the rate of energy transformation is the most important defining quantity for a lamp.

Primarily, then, the fundamental relation for an incandescent

lamp lies between its light radiation or illuminating power and the energy producing it. Both Abney * and Siemens † early investigated the dependence of the radiations from the filament on their influencing factors. Later an approximate relation was proposed defining the illuminating power to be proportional to the cube of the energy transformed.

In what follows, $P$ will denote the illuminating power in appropriate units, and $E$ the energy in watts, while $m$ and $n$ are equating constants. The approximate formula is:

$$P = mE^3. \tag{74}$$

Götz ‡ objected to this formula and stated that a curve platted to the formula

$$P = nE + mE^2 \tag{75}$$

conformed very closely to experimental values.

Working from the exponential formula

$$P = mE^x, \tag{76}$$

Ferguson and Center § obtained values for $m$ and $x$ which varied greatly with the lamp tested. They assumed that the coefficient $m$ remained unchanged in value for all degrees of incandescence. That this is not the case will be shown later.

For a lamp rated at 110 volts and 16 candles, they found

$$P = 98 \times 10^{-5} \times E^3. \tag{77}$$

And similarly for another lamp rated at 100 volts and 20 candles,

$$P = 110 \times 10^{-6} \times E^{2.7}. \tag{78}$$

Weber ‖ noted that his measurements conformed fairly well to equation 74 stated above. He did not find the coefficient

* Proceedings of the Royal Society, 37, 1884, page 157.

† British Association Reports, 1883, page 425.

‡ Centralblatt für Elektrotechnik, V, page 720.

§ Technology Quarterly, 1891, page 147.

‖ H. S. Weber; ref. cit., page 198.

$m$ to have an extendedly constant value, but in general it increased with the intensity of the illumination.

**191. The relation between the illuminating power, the current, and the electromotive force.** — In applied photometry, as well as the practice of lighting with incandescent lamps, regulation is had almost entirely with reference to the voltage; the relation, then, which changes in the illuminating power have to the voltage-change is important.

Again, as in the case of the energy the relation of illuminating power to volts is given with sufficiently close approximation by the equation:

$$P = aV^x, \tag{79}$$

$V$ denoting the volts and $a$ being an equating constant.

Ayrton and Medley * gave as the result of certain measurements

$$P = aV^{5.91}. \tag{80}$$

Ferguson and Center † found in this case

$$P = 62 \times 10^{-14} \times V^{6.6}. \tag{81}$$

They also determined the value of the relation between illuminating power and current, obtaining

$$P = 520\ I^{5.1}. \tag{82}$$

This last result follows from the same method of analysis outlined above.

The most noticeable fact brought out by these results is the lack of comparableness of filaments under any one set of conditions. The cause of this must be in the filament itself, and the physical nature of such carbon is evidently complex and not within exact control.

To illustrate these various relations, data are here given, obtained from an incandescent lamp which, at 104 volts, was

* Philosophical Magazine, May, 1895, page 421.

† Ferguson and Center ; ref. cit.

nominally rated to yield 16 candles. Curves platted from these data are shown in Figure 48.

| Volts | Milliamperes | Watts | Candle power | Watts per c. p. |
|---|---|---|---|---|
| 65 | 348 | 22.6 | 0.8 | 28.3 |
| 67 | 370 | 24.7 | 1.3 | 19.1 |
| 69 | 380 | 26.2 | 1.5 | 17.5 |
| 71 | 390 | 27.7 | 1.8 | 15.37 |
| 73 | 401 | 29.2 | 2.2 | 13.35 |
| 75 | 412 | 30.9 | 2.6 | 11.9 |
| 77 | 425 | 32.7 | 3.0 | 10.9 |
| 79 | 438 | 34.6 | 3.6 | 9.6 |
| 81 | 450 | 36.4 | 4.2 | 8.68 |
| 83 | 461 | 38.2 | 4.85 | 7.88 |
| 85 | 472 | 40.1 | 5.65 | 7.1 |
| 87 | 486 | 42.3 | 7.00 | 6.04 |
| 89 | 497 | 44.2 | 8.00 | 5.54 |
| 91 | 508 | 46.3 | 9.2 | 5.03 |
| 93 | 516 | 48.0 | 10.2 | 4.70 |
| 95 | 529 | 50.3 | 11.05 | 4.55 |
| 97 | 541 | 52.5 | 12.6 | 4.16 |
| 99 | 552 | 54.6 | 14.5 | 3.76 |
| 101 | 564 | 56.9 | 16.3 | 3.44 |
| 103 | 575 | 59.2 | 18.0 | 3.29 |
| 104 | 580 | 60.3 | 18.8 | 3.20 |
| 105 | 586 | 61.5 | 20.2 | 3.05 |
| 107 | 597 | 63.9 | 22.0 | 2.90 |
| 109 | 608 | 66.3 | 25.5 | 2.60 |
| 111 | 620 | 68.8 | 28.0 | 2.45 |
| 113 | 631 | 71.3 | 30.5 | 2.34 |
| 115 | 642 | 73.8 | 32.7 | 2.25 |
| 117 | 653 | 76.4 | 35.5 | 2.15 |
| 119 | 665 | 79.2 | 39.3 | 2.00 |
| 121 | 680 | 82.3 | 43.0 | 1.91 |
| 123 | 690 | 84.9 | 47.5 | 1.79 |
| 125 | 703 | 87.9 | 50.0 | 1.76 |
| 127 | 717 | 91.1 | 55.0 | 1.65 |

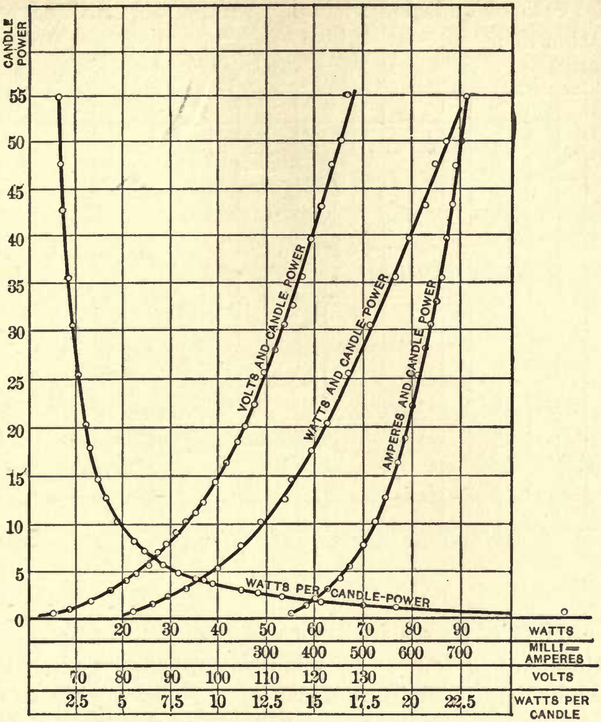


FIG. 48.

**192. The life characteristics of the incandescent lamp.** — The curve of the maintenance of illuminating power throughout the life of the filament is a valuable indication of the extent to which the physical condition of the filament has changed. In the same connection the energy curve for the unit of illuminating power affords some indication of the maintenance of the rate of emission of radiations from the filament. In this case the measure of the light radiated is taken as an approximate measure also of the dark, or heat, radiations. But the light and heat radiations are not functions of each other, so the curve of watts for sustained candle power does show a change

in the rate of emission without affording a quantitative determination of it.

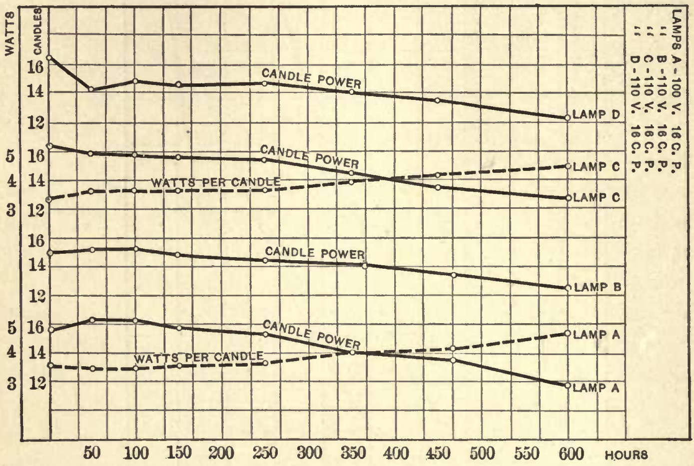


FIG. 49.

A number of curves are shown in Figure 49 for a test extending through 600 hours. New lamps were employed, and maintained in continued incandescence, and the voltage was kept practically constant at the marked values for the lamps. The lamp *A* was rated for 100 volts, the others for 110 volts, and each had a nominal illuminating power of 16 candles. The lamp *A* to a marked extent, and the lamp *B* to a less degree, exhibit an initial increase of illuminating power, which reached a maximum value between 50 and 75 hours. This was followed by a continuous decrease, but the decrement was not uniform until 300 hours had elapsed. It is very noticeable in all the curves that the epoch from 150 to 250 hours is characterized by the least slope of curvature, or the illuminating power is more nearly uniform during this epoch than any other. In contrast with the curves from lamps *A* and *B*, the curve from the lamp *C* exhibits a continual decrease in illumi-

nating power. In the lamp *D*, the initial illuminating power fell off rapidly and then increased as quickly, until the illuminating power was partially recovered; thence the curve in general resembles the others.

The filaments of the lamps whose life curves are marked *A*, *B*, and *C*, were of the squirted cellulose varieties. Lamps *A* and *B* were from the same maker.

The following details have been furnished by the manufacturers of these lamps: *

"The purest obtainable form of cellulose [*A* and *B*, cotton] is dissolved in a solution of zinc salts [*A* and *B*, $ZnCl_2$], which at the proper temperature forms a stiff, gluelike liquid. This liquid is forced through a glass die into a glass jar containing an alcoholic coagulating solution [*A* and *B*, alcohol], when it hardens into a thread, resembling vermicelli, which coils upon a plate near the bottom. When a sufficient length of thread has been squirted, it is removed and washed thoroughly in much the same way that a photographic plate is cleansed after development. After washing out the soluble zinc salts and the alcohol, nothing remains but non-fibrous or amyloid cellulose in the form of a soft thread. In this stage it is weak and tears readily. The thread is then wound upon reels and allowed to dry at a constant temperature. In drying an enormous shrinkage occurs, the diameter of the thread being reduced to about one-fourth that of the die through which it was squirted. The size of the thread suitable for each kind of lamp is controlled by the size of the die.

"These dried threads are then wound upon forms of a size and shape to give the requisite number of coils of proper diameter for the filaments desired.

"The wound forms are next placed in graphite boxes and surrounded with powdered carbon. The boxes are subjected to a

* The writer acknowledges his obligations to the courtesy of the manufacturers of these lamps, especially to the company making lamp *C*, by whom this description was furnished.

temperature sufficient to soften platinum in a furnace which is slowly heated until the highest point is reached. The heating requires about eighteen hours, and must be very gradually applied until the hydrocarbons are removed from the thread, otherwise they will melt together.

"After the baking, nothing remains but pure carbon, weighing about one-fourth as much as the threads, and representing the fixed carbon of the cellulose. In this condition the carbons resemble a japanned steel spring. They are very hard and elastic, though brittle, and are quite uniform in size and resistance. A coating of carbon is deposited upon these carbon wires by heating them electrically in the vapour of a liquid hydrocarbon [*A* and *B*, gasoline]. As the deposition or treatment of each carbon is under control, the current is cut off automatically when the diameter and resistance have both reached the points suitable for the kind of lamp for which it is designed. After 'treating,' the colour of the filament is a steel-gray, due to a coating of what is probably graphitic carbon."

The filament which yielded the best results in these tests was of the cellulose type, made in the usual manner by dissolving cotton in a solution of $ZnCl_2$, and then squirting this under air pressure through a die, into alcohol. After the artificial thread was carefully washed and dried on a drum, it was wound on a form and carbonized in the usual manner, and finally flashed in gasoline vapour.

The first three curves indicate careful manufacture and satisfactory flashing, while the last curve shows an unstable condition of its filament, characteristic of faulty manufacture.

The subject of life tests on incandescent lamps has been frequently and widely experimented upon with fairly uniform results when the tests have been scientifically conducted. Especially interesting tests have been made by Prof. B. F. Thomas* in 1892, and Prof. Ayrton† and E. A. Medley in 1894.

* B. F. Thomas; Transactions American Institute of Electrical Engineers, 1892, page 271.

† Philosophical Magazine, 39, 1895, page 389.

## THE INCANDESCENT CARBON FILAMENT AS A PRIMARY STANDARD OF LIGHT

**193**. We have already seen an attempt made to employ incandescent platinum in mass or in foil for a primary standard of light. As early as 1857 Zöllner * experimented with incandescent platinum wires for the purpose of studying the light radiation from them; but these studies were barren of any definite photometrical results. Upon the advent of the incandescent lamp, it was early looked upon as a possible light standard. In 1885 a committee of the British Association † brought forward in a resolution that, "a unit of light is obtained from a straight carbon filament at right angles to the middle of the filament, when the resistance of the filament is one-half of its resistance at $0^0$ Centigrade, and when it consumes $10^9$ c. g. s. units (100 watts) of electrical energy per second." It was further proposed ‡ to make a large number of subjective experiments on human eyes to obtain a coefficient or multiplying quantity for the expression of the illumination from the standard lamp, by the change in the resistance of the filament. In such manner, when comparing lights or sources of illumination, the standard filament might be adjusted until the spectrum curve of its radiation should be that of the light compared. Then the total heat and light radiations of the illuminating source and the standard lamp could be compared at equal distances by means of a thermopile. From the known radiant properties of the standard lamp, established by researches on the standard filament, the compared light could be completely defined. Abney § had already proposed the definition of a standard of white light by experimentally establishing formulas which should connect the radiation from the filament with its

* Poggendorff's Annalen, 100, 1857, pages 381 and 109; 1860, page 256.

† British Association Report, 1885, page 63.

‡ Reference cited, page 83.

§ British Association Report, 1883, page 422.

energy, current, electromotive force, resistance, and temperature quantities. He proposed the adoption of a standard spectrum for the comparison of the quality of lights, the quantity to be determined photometrically.

The dimensions of the carbon filament and the electrical quantities involved in its operation are all capable of ready and exact determination. It would thus seem to be admirably adapted for a standard light, or an absolute photometrical standard, in the sense that its light radiation might be completely specified by reference to the dimensions of the filament and its temperature of operation. Further, such a standard as was pointed out in the British Association Report, would be exceedingly flexible, and not only capable of adjustment to agree in quality with the compared lights, but from the continuous nature of the spectrum of carbon, at a certain temperature, it would conform to the requirements for normal quality of light. Certainly no source of illumination as yet proposed for a standard light has so many obvious advantages.

The failure of the incandescent lamp to fulfil its promise of becoming an exact standard of light has been due to a lack of reproducibility and of constancy in its physical character when in operation. Though it would seem to be difficult to determine accurately the area of radiating surface, yet doubtless this could be accomplished were it the only obstacle. The essential difficulty results largely from the tendency of carbon to assume an allotropic form at very high temperatures. It is seemingly impossible to produce homogeneous carbon filaments or to flash filaments until the surface assumes known radiating qualities.

It has been seen that the presence of graphitic carbon greatly modifies the temperature change of resistance, so that the specification of a certain change of resistance to define the temperature is not feasible. The proposition that the operating temperature shall be defined by a decrease of the resistance to one-half of its value at 0° Centigrade, loses all certainty through the lack of homogeneity in the filament. A further difficulty is introduced by the rapid change of resist-

ance due to hysteresis and the slow progressive one due to molecular readjustment.

The variation in the emissivity, both in the same filament and between different filaments is an additional uncertainty. Add to these the influence of the blackening of the chamber walls, their indefinite absorption, and the vaporization of the filament, and the causes for the failure of this promising standard are apparent. The failure, briefly, lies in the inability to establish the light emitted as a function of the dimensions and physical properties of the filament.

### THE INCANDESCENT LAMP AS A COMPARISON LIGHT

**194.** Before the advent of the incandescent lamp in a perfected commercial form, there was no certainty in the successively repeated light values of the primary and comparison flames then used. And further, the light strength at different times during any one burning of a light was not certainly comparable in a series of values. Attention has already been called to this in a previous chapter, and the opinion was there expressed that much of the error and discrepancy in the literature of photometrical standards and tests has originated from such uncertainties.

Though the incandescent lamp disappointed those who anticipated finding in it a primary standard of light, principally from the failure to establish a constant relation between the illuminating power and defining dimensions and physical conditions, yet the incandescent lamp has probably been of greater service photometrically than any other light source. This service has been done through the constancy of the illuminating power of a particular filament under proper conditions, which has made possible both concordant data and a quantitative knowledge of the variation in flame standards.

Among the first, Preece* in 1884 suggested the use of a

* Proceedings Royal Society, Vol. 36, 1884, page 272.

small incandescent lamp for a portable photometer. Later, the reliability of this light as a secondary standard was established by Lummer and Brodhun.* At this time these scientists were engaged in an investigation of light standards, especially of the amyl acetate lamp and flame. Before employing the incandescent lamp as a reference light, they carefully studied its photometrical qualities. The colour of the amyl acetate flame being reddish, the colour of the light of the incandescent lamp was accommodated to it by operating the lamps at a reduced voltage. Two 65-volt lamps were operated at a constant pressure of 55 volts, the electricity being supplied by a storage battery. Of the two lamps so tested, one styled *R* was burned continuously, while the other one, *L*, was operated at certain intervals. They were compared against one another at frequent intervals, being placed as the two lights on the photometer bar. The data obtained were: —

| Hours burned | | Ratio $\frac{L}{R}$ |
|---|---|---|
| R | L | |
| 1 | 1 | .8779 |
| 20 | 2 | .8764 |
| 62 | 3 | .8741 |
| 154 | 8.5 | .8724 |
| 211 | 13.5 | .8677 |

In these tests especial accuracy was sought in the measurement of the current and potential of the lamps. Under their normal conditions of burning, the light energy of the lamps varied nearly ten times as rapidly as the electrical energy, in consequence an error of .05 per cent in the measurement of the electrical quantities would affect the light strength about .5 per cent at normal candle power.

The conclusion derived from these tests was that incandes-

* Zeitschrift für Instrumentenkunde, 1890, page 121.

cent lamps under proper electrical conditions proved especially constant light sources. In addition they possess two excellent properties: the colour of their light may be adjusted to that of the compared light, and they are portable on the photometer bar without disturbance of their illuminating power.

**195. The working conditions** for incandescent lamps employed as secondary photometrical standards have been fully outlined in the discussion of the physics of the incandescent lamp.

When employed merely for the purposes of comparison there is no necessity for a careful determination of the illuminating power. Used as a secondary standard, the illuminating power is to be determined by reference to the amyl acetate or pentane flames, the proper corrections for humidity, etc., being made. It is well to standardize a number of lamps, reserving one or more for checking lamps in more frequent use. Obviously it is necessary to standardize a lamp in a certain marked position with reference to the plane of the photometer screen, and in its subsequent use this relation, once selected, is to be maintained in all cases.

**196. Sensitiveness in measurement.** — By differentiating the equations between the illuminating power, and the energy, current or potential (page 180), the rate at which the illuminating power changes with respect to any one of these variables, is given. Also, by referring to the curves for these relations (Fig. 48, page 183), the change in illuminating power for a given change in any one of the electrical quantities may be immediately derived. These results emphasize the need for very great sensitiveness as well as accuracy in the measurement of the electrical quantities.

**197. Precautions** are needed to avoid the influence of *temporary set,* or hysteresis in the resistance of the filament (page 175), and especially the *permanent set* due to abnormally high voltage. After a lamp has been calibrated it should not have

a pressure impressed upon it in excess of the voltage at which it was calibrated. This is in the nature of a general observation, for in particular cases it may be found desirable to calibrate a lamp over a considerable range of pressure, and plat a curve for it and use the lamp accordingly.

Except for the comparison of lights of reddish tinge, it is not necessary, nor is it even desirable, to use an incandescent lamp as a secondary standard at any temperature short of that which will produce a clear white light. A carefully selected lamp will usually prove as constant at such a temperature as when operated at a lower temperature and emitting a reddish light.

Further, the life curves show that new incandescent lamps, as a rule, are not suitable for light standards, nor do they become so until they have burned a sufficient number of hours to render their illuminating power practically constant. Generally, after burning one hundred and fifty or two hundred hours they attain this desirable stability.

Overheated lamps, lamps with blackened bulbs, and lamps with rough and dull black filaments are not suitable for photometrical purposes. Only the product of a reliable factory, where careful attention is paid to every detail of manufacture of the filament, and thorough exhaustion of the chamber is accomplished, should be selected. The filament should be slowly flashed and present a smooth, hard, bright gray surface. Lamps which initially burn with a bluish tinge are to be avoided; the vacuum in such cases is not sufficiently good to insure the desired constancy in the filament.

**198. The advantages** of the incandescent lamp as a secondary or reference standard of light are, briefly: the constancy of the illuminating power in operation; the constancy of the illuminating power in frequent reproduction; freedom from the influence of atmospheric conditions so disturbing with flames; flexibility in accommodating the quality of the light over a wide range from the reddish tinge of many flames to the blu-

ish cast of the arc light; the ability to produce the requisite quality for normal white light; its cheapness, convenience, and simplicity; and finally, the accuracy with which it is possible to measure and control the electrical quantities involved in its operation.

## OIL AND GAS LAMPS

**199. Petroleum burning lamps.** — In 1869 Rüdorff* employed as a comparison light, for the study of the standard candle, an argand burner, with the usual glass chimney, and oil as a combustible. Similar lamps were employed by Siemens and Hefner-Alteneck,† and as a calibrated reference standard in the Edgerton photometer.‡ In this latter case only a portion of the flame was used, the screening being accomplished by a movable diaphragm, somewhat on the principle of the Methven screen.

A petroleum lamp is only fairly satisfactory for such purposes; it is open to all the objections urged against the carcel lamp. The gradual increase in flame length, the charring of the wick, and fouling of the chimney render frequent calibration of the flame necessary. Before the knowledge of flame standards became so exact, certain early experimenters considered such lamps to be convenient and reliable for purposes of comparison.

The colour of the flame is too yellow for use in the photometry of incandescent lamps. In contrast with the superiority of the incandescent lamp for such uses, the petroleum lamp is both uncleanly and unreliable.

**200. The keats lamp.** — This is an English form of the carcel lamp, burning sperm instead of colza-oil. For some time it was thought to have certain advantages as a primary standard, but was soon relinquished for this purpose and employed only

* Schilling's Journal, 1869, page 283.

† Elektrotech. Zeitschrift, 1883, page 454.

‡ Dingler's Polytech. Journal, 229, page 48.

as a comparison light. It has been carefully studied by W. J. Dibdin.* Its properties are so similar to those of the carcel lamp they require no further discussion.

**201. The benzine lamp.**† — Benzine, uncombined with other combustibles, has been used, to a limited extent, in simple spirit lamps. As a secondary standard it has proved quite constant and reliable, and has the additional merit of burning with a fairly white flame. It is employed in such a capacity in the Leonhard Weber (page 81) portable photometer.

**202. Argand and simple jet gas flames.**‡ — These lights have been frequently discussed, both directly and indirectly, especially under the topics of the Methven screen (page 126) and the pentane lamp (page 132). Used by themselves, or in connection with a screen, they are fairly reliable reference lights, and, under proper conditions, may burn with steadiness, though they require frequent calibration.

**203. Acetylene.** — The fitness of this gas for furnishing a primary standard of lighth as been studied to some extent.§ No definite results have been accomplished, and no conclusion regarding its photometrical fitness can be arrived at in advance of satisfactory experimental evidence. Judging from the experience with the pentane air-gas standard, the design of a compact and portable apparatus will prove especially difficult. Another difficulty will be the prevention of the fouling of the burner.

The gas burns with a white and brilliant flame, whose colour

* Journal for Gas Lighting, 45, 1885, pages 568 and 625; also consult Vol. 38, 1881, page 719.

† Elektrotech. Zeitschrift, 1883, page 455.

‡ Consult Journal for Gas Lighting, 54, 1889, page 968.

§ Violle; Comptes Rendus, 112, 1896, page 507; and June, 1899. Also, "A Study of the Gas Flame from Acetylene," L. W. Hartman, Physical Review, September, 1899, page 176.

is admirably adapted for photometrical purposes. The correction factors for humidity and atmospheric pressure remain to be determined. That the high temperature of the acetylene flame would indicate that the correction for humidity will prove small, does not follow: for the amyl acetate flame is less affected by moisture than the pentane flame, which burns at a higher temperature.

Acetylene being a simple gas, and not a mixture, can be obtained in a state of great purity, from mineral carbides, and thus meets the chemical requirements for a standard combustible. It promises to become an open-flame standard of great merit; but, until this is proven, it is only suitable for photometrical work in the capacity of a comparison light.

At the present time a number of investigations are in progress to define the photometrical properties of the acetylene flame for use as a primary standard.* In the physical laboratory of Cornell University such investigations are being accurately and exhaustively pursued, and their conclusion may be anticipated to define the chemical and illuminating properties of the gas, and establish the necessary correction factors for its flame. The design of suitable apparatus and an appropriate burner are also elements in these investigations. The results already obtained are of a promising character, and justify the anticipation that a working primary standard of light may soon be developed.

* The author desires to express his obligations to Dr. E. L. Nichols for acquainting him with the experiments he is conducting and granting permission for the publication of this note.

# CHAPTER VI

## THE PHOTOMETRY OF THE INCANDESCENT LAMP

**204. The light distribution from an incandescent lamp** is a function of the shape of the filament (page 188), and this will differ amongst lamps to the extent that their filaments fail of similarity in shape. Such statements are based on the assumption that the intrinsic brightness of the incandescent filament is uniform throughout its length, which is practically the case if they have been properly flashed.

The comparison of the illuminating power of incandescent lamps is very generally based, and exclusively so commercially, on measurements made at one point in the horizontal plane. When all the filaments are similarly placed, such measurements have a certain value; but these data can only refer to the luminous intensity in that particular vectorial direction, and unless factors are known which will connect the intensity along any other vector with that measured, such single values are of little practical or theoretical importance.

Comparisons of illuminating power obtained in this manner are obviously doubtful. The variations in the shape of filaments are so marked that the proper comparison of their illuminating power follows only from values of their average spherical light distribution. In no other way can the efficiency of the lamp be determined, for this is properly a ratio between the total light radiated and the energy transformed in the filament.

Usually the illuminating power of a filament is graphically defined by five curves, giving the distribution in the horizontal plane and in four vertical circles with azimuths of 0°, 45°, 90°,

and 135°. The azimuth is reckoned from the prime meridian, which is defined by the vertical plane through the photomet-

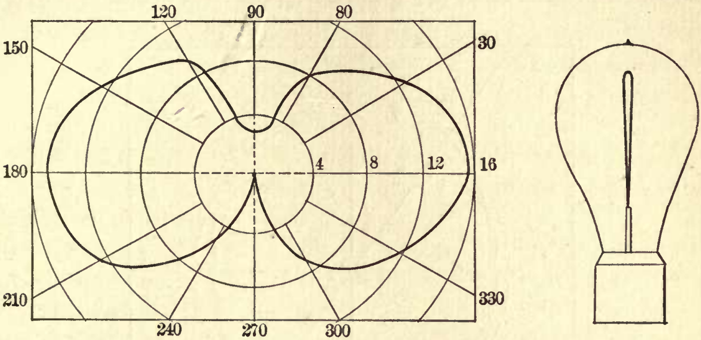


FIG. 50.

rical axis, when the lamp is in its standard or marked position, with the plane of the filament normal to the photometrical

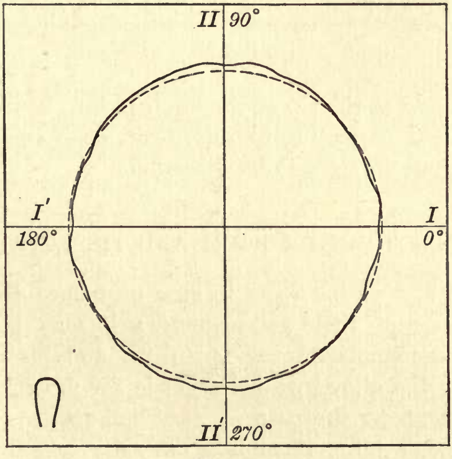


FIG. 51.

axis. In the illustrations a curve for the distribution of the light in a vertical plane is shown in Figure 50, and both the

shape and position of the filament are indicated; while the distribution in the horizontal plane, of filaments whose shape is sketched in each case, is given in Figures 51 and 52.

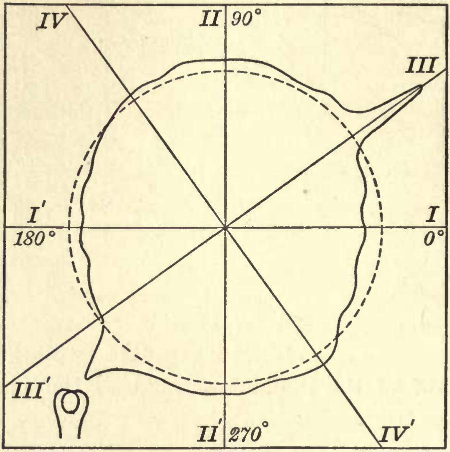


FIG. 52.

The intensity at the tip of the lamp is low, because the area of the filament projecting in this direction is small; the base entirely screens all light in its direction.*

## THE PHOTOMETER ROOM AND ITS APPARATUS

**205.** The size of the room in case no flames are used photometrically is of little consequence; it may be just large enough to accommodate the apparatus and leave space for operating it, due allowance being made for proper ventilation. When, as must be the case in most laboratories, flames are photometered, a large room is a necessity in order to insure

* An admirable paper by Liebenthal on "The Light Distribution and the Photometry of the Incandescent Lamp," may be found in Zeitschrift für Instrumentenkunde, 19, 1899, pages 193 and 225.

uniform conditions of the aqueous and carbon dioxide contents of the air, without marked drafts, such as would be occasioned by rapid ventilation in a small room.

For the general practice of arc and incandescent lamp photometry, a suitable room would have its dimensions of some twenty feet in length and ten feet or more in width, and would preferably have a high ceiling.

The room should be entirely darkened when measurements are made. To this end outside windows should be permanently darkened or provided with inside solid wooden shutters, so fitted that no light will leak past them. It is well to vestibule the doorway leading into the room, as is frequently done in photographic dark rooms.

All surfaces in the room are to be blackened that they will absorb all light falling upon them; and all the light reaching the screen should be radiated directly from the light sources or from the reflecting mirrors, and not from irregularly reflecting surfaces about the room.

The walls and woodwork may be painted black, employing a paint which dries with a dull black finish; for a bright finish even with black paint would make a partially reflecting surface; or, they may be coated with a black wash. This wash is made with fine, clean lampblack and glue water.

The chairs, tables, and other furniture, and as well, all switches and fittings should be finished with a dull black surface. The manufacturer will furnish all parts of the photometer bench thus finished, but accessory apparatus, such as voltmeters, should be encased in black. The floor is often neglected after having taken the most elaborate precautions with the walls and apparatus. In a very small room the floor may be left unpainted, but unless certain that no light can be reflected from it to the screen, it is advisable to coat the floor with a black stain.

The judgment in individual cases will indicate how far to carry out these precautions, provided it is based on experience.

Such elaborate attention to the prevention of reflection of

light would also suggest that the pains be taken not to place white paper or other like objects where they may act as reflectors.

206. **The photometer bench** is usually mounted on a firm, heavy table, especially looking toward the protection of flames from mechanical disturbances. The operating side of the bench is placed quite close to the edge of the table, though it is convenient to have the table considerably wider than the bench, to accommodate instruments, rheostats, and other accessories.

207. **A permanently wired** table is advisable. The wiring should provide connections for a working incandescent lamp at each end of the bench, and a small reading lamp to be placed

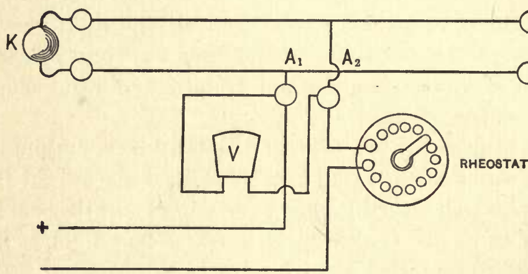


FIG. 53.

on the screen carriage. Attachments for a voltmeter should be provided for each working lamp, as close as possible to the terminals of the lamp. It is also convenient to place a switch at the centre of the table and within easy reach of the operator for each of the three lamps. Connections should also be left in each main lamp circuit for the regulating rheostats. A plan for wiring is shown in Figure 53, which necessitates but one voltmeter.

208. **A reading lamp** attached to the carriage carrying the screen will prove a great convenience. This lamp should be of low light power so as not to affect the eyes of the observer. A

lamp with a cylindrical bulb may be used, and this is to be fitted with a metal reflector, to throw the light on the scale bar, and at the same time shade the observer's eyes from the direct light. The lamp is only lighted when a reading is made.

**209. A canopy** of some description should be arranged to shield the operator's eyes from the lights under comparison. Black plush, or velvet, is a suitable light-proof material for such a canopy, and it may be attached to a wire frame which is either fastened to the screen carriage or to some special carriage which shall be moved by that carrying the screen. The frame if too large would limit the travel of the screen. The canopy should entirely surround the screen and have lateral openings in the photometer axis slightly larger than the openings in the screen box; but at no position on the bar should the canopy cut off light from the screen.

Some photometricians prefer to screen the comparison lights with canopies. This is a matter of no consequence when incandescent lamps are used, but with open flames a canopy enclosing them is objectionable, as it interferes with the adjustment of the flame, and by even partially confining it, may alter its value (page 121).

In some instances wooden canopies are built about the lamps, and small pieces of coloured glass are inserted for viewing the lights. The use of all coloured glass in photometrical practice is to be avoided, as it gives a persistent colour cast to the eye, which may introduce an error when adjusting the screen. Coloured glass is needed for viewing the electric arc, but this should never devolve upon the observer at the screen.

**210. The rheostats** used with the incandescent lamps should afford very close adjustment of the voltage over a considerable range. This is accomplished by using two rheostats with each lamp. Each rheostat should have numerous steps, the one with a high resistance to the step and the second with very

low resistance intervals, but having a total resistance slightly in excess of the resistance interval of the first rheostat. This will insure sufficiently sensitive adjustment. Circular enamel rheostats are well adapted for this work.

211. **The source of electromotive force** for incandescent lamp photometry should be the storage battery. The illuminating power of the incandescent lamp is so sensitive to slight changes in voltage, that a very constant source of electromotive force is needed in its photometry. A very steadily-running dynamo may answer fairly well, provided it supplies current only to the photometer room. Though a battery of even small cells will be the most expensive item in the equipment of the photometer room, its installation is advisable when accurate work is attempted.

212. **The sensitiveness of the voltmeter and the ammeter.** — From the discussion of the illuminating power as a function of the volts, amperes, or watts (page 180), and an inspection of their graphical relations (Fig. 48), the necessity for great sensitiveness in the instruments measuring these quantities, and for the accurate calibration of their scales, is seen.

Careful attention to these details is imperative; but the photometrician should not be content with generalizations in such matters, but be able to subject them to specific calculation.

Where such great sensitiveness and high accuracy are needed, the calibration should not be left wholly with the manufacturer of the instruments, but be carefully verified by the photometrician himself; and this should be done frequently to insure confidence in the accuracy of the scale readings. The potentiometer method is especially recommended for the calibration of both the voltmeter and the ammeter, being accurate and readily applied.*

* "Electrical Measurements," Carhart and Patterson, p. 205.

**213. A calculation of sensitiveness.** — The data for this calculation are obtained from the table on page 182, corresponding to the curves of Figure 48.

The equation between the candle power and the volts is (page 181)

$$P = aV^x. \tag{79 bis}$$

To find the value of the exponent $x$ the equation is given the logarithmic form twice, —

$$\left.\begin{aligned}\log. P_1 &= \log. a + x \log. V_1.\\ \log. P_2 &= \log. a + x \log. V_2.\end{aligned}\right\} \tag{83}$$

From these equations by elimination of *log. a*,

$$x = \frac{\log. \dfrac{P_1}{P_2}}{\log. \dfrac{V_1}{V_2}}. \tag{84}$$

For the solution of the equation, observed values are taken, which are characteristic and sufficiently wide apart. From the table are selected, $V_1 \equiv 115$; $P_1 \equiv 32.7$; $V_2 \equiv 95$, and $P_2 \equiv 11.05$, from which by substitution in equation 84,

$$x = 5.7.$$

Similarly between the observations at 85 and 105 volts,

$$x = 5.9,$$

and between 101 and 109 volts,

$$x = 5.78.$$

Taking 5.8 as a working value for $x$, the equation reads

$$P = aV^{5.8}. \tag{85}$$

For the purpose in hand, the constant $a$ will be calculated for 104 volts and 18.8 candle power, and the value is found to be,

$$a = 37 \times 10^{-14}.$$

The general equation for this particular lamp is now completely known, and is

$$P = 37 \times 10^{-14} V^{5.8}. \tag{86}$$

**214. The potential sensitiveness** of the candle power, or the candle-power-voltage rate of change is found by differentiating equation 86. Then

$$\frac{dP}{dV} = (5.8 \times 37 \times 10^{-14}) V^{4.8}, \tag{87}$$

from which a curve of sensitiveness can readily be calculated and platted.

A particular value of the sensitiveness will be sought for 104 volts and 18.8 candles, in order to find the change in volts to produce a change of the one-hundredth part in the illuminating power. This is found by solving for $\Delta V$, $\Delta P$ being taken at 0.188.

$$\Delta V = \frac{0.188}{5.8 \times 37 \times 10^{-14} \times 104^{4.8}},$$

which yields

$$\Delta V = 0.18 \text{ volts.}$$

**215. The application** of these results shows conclusively the necessity for a sensitive and accurately calibrated voltmeter, for the scale must be read to 0.18 volt with certainty, for an error-limit as great as one per cent in the illuminating power.

The sensitiveness required in the ammeter or wattmeter, if one is used, can be calculated in a similar manner.

**216. Adjustable lamp holders.** — The complete photometrical study of the incandescent lamp will include the distribution of its light in the horizontal or equatorial plane, and in certain of the meridian planes of the filament; thus the spherical distribution of light may be arrived at when a large number of properly disposed measurements have been made, the distribution being referred to the optical centre of the filament. These are the conditions governing the design of any device

for holding the lamp in the proper positions for such measurements; or, geometrically, the lamp must be capable of the angular adjustment of its position in both the azimuth and meridian planes, with reference to the optical centre of the filament. The device for meeting these conditions is so readily apparent and so simple that practically all holders are of one type.

Amongst the earliest forms of the device was the lamp holder used in the Franklin Institute tests.* Later this was given its present form by C. Heim,† (Fig. 54).

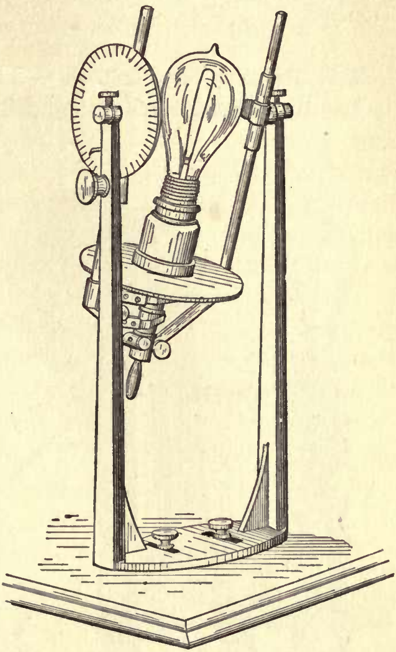

FIG. 54.

As such holders are now made, the lamp is carried by a vertical spindle bearing a circularly divided azimuth scale, and furnished with a clamp for setting the lamp in any desired azimuth. This arrangement is borne either by a yoke, or by a curved arm pivoted to move in a plane at right angles to the azimuth plane, or in a meridian plane, and which may be firmly clamped in position about a second circularly divided scale which indicates the angular inclination of the equatorial plane of the lamp to the horizontal.

* Report on the Efficiency and Duration of Incandescent Electric Lamps, Franklin Institute, 1885, page 14.

† Elektrotech. Zeitschrift, 1886, page 384; also 1887, page 358.

The spindle carrying the incandescent lamp is adjustable vertically so as to bring the optical centre of the filament in the axis of the curved arm; and when the lamp is placed in the holder it must be adjusted accurately to meet this condition.

**217. Rotating lamp holders.** — The spinning of the filament is readily accomplished by slightly modifying such a holder. The pivot of the curved arm is hollowed to receive a spindle carrying two small pulleys. A light belt passes from the inner pulley, and is deflected by two idle pulleys placed at the bend of the arm, and then passes around a fourth pulley on the lamp axis of the holder, which in this case becomes a light vertical shaft. The outer pulley on the horizontal shaft is belted to a small electric motor for driving the arrangement.

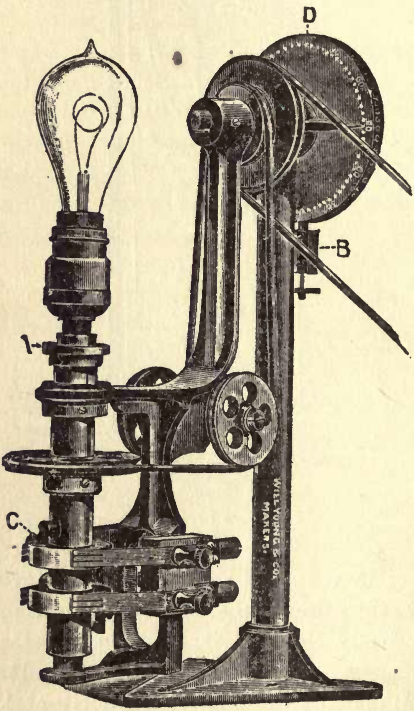

FIG. 55.

The lamp spindle carries slip rings for maintaining the electrical current. A rigid device for clamping the curved arm in any desired position completes the apparatus. A rotator recently designed by Elmer G. Willyoung (Fig. 55) has an additional pair of brushes for the

voltmeter terminals, so that the potential difference at the lamp itself may be measured, thus avoiding the drop of potential over the main contacts.

The essentials of such an apparatus are solidity of all its parts and excellent balance, that it may operate at a high speed without vibration.

**218. The proper working length of the photometer bar** is a matter to be determined in individual cases, depending upon the size of the lamps photometered and the degree of sensitiveness desired in the measurements. The maximum sensitiveness with any bar occurs when the screen is in balance midway of the lights compared. In general, for any setting increased sensitiveness follows an increase of the distance between the compared lights.

In the photometry of incandescent lamps of ordinary illuminating power, a working distance between the compared lamps of 100 centimetres may be used, but a distance of 150 or 200 centimetres is to be preferred. Probably the most generally useful and the advisable free length of the bar is 250 centimetres, or 100 inches.

**219. The graduation of the bar.** — Two classes of scales may be engraved on the bars: one is the equally divided scale, while the other is a proportional one. Each millimetre division of the metric scale should be engraved; and when the bar is divided into inches each tenth-inch only need be engraved, as smaller divisions can readily be estimated.

**220. The proportional scales** are based on the general photometrical law:

$$I_c = \frac{(L-l)^2}{l^2} I_s, \tag{88}$$

$l$ being the distance from the standard whose intensity is $I_s$ to the screen. A proportional scale will enable the intensity $I_c$ of the compared light to be read directly from the scale, provided it has been adjusted to a certain value for $I_s$.

**221. The calculation of proportional scales.**—Some imported photometers have, in addition to a metric scale, a proportional one from which German candle power (Kerzen) may be read directly when the amyl acetate standard is used. In this case, $I_s \equiv 0.833$, being taken, a few properly selected values for $I_c$ may be assumed and the equation

$$I_c = 0.833 \, \frac{(L - l)^2}{l^2} \tag{89}$$

then solved for the corresponding values of $l$. From these values a curve may be platted, and from the curve the entire scale may be laid out.

Confining the discussion to ordinary practice with a standard incandescent lamp, it is clear that a permanent proportional scale, engraved on the bar, will require the readings to be multiplied by a factor, the ratio $\frac{I''_s}{I'_s}$ in case a standard lamp of intensity $I''_s$ is used when the scale was designed for direct reading with a standard of the value $I'_s$.

A very satisfactory method avoids the use of a permanently marked proportional scale for a temporary one based on the value of the standard lamp in use at the time. This may be calculated entirely, or may be marked by the graphical method just given.

A hard-wood bar may be attached to the rail with a strip of paper fastened on it, which can then be directly marked off from the graduated scale to conform with the divisions calculated. By attaching an auxiliary index finger to the travelling carriage both scales may be read simultaneously.

A second variety of proportional scales, *the ratio scale,* may prove convenient. This is based on serial values for the ratio of two lights. It is calculated by solving equation 88 for $l$. Writing

$$\frac{I_c}{I_s} = P \tag{90}$$

and substituting this in the equation,

$$\sqrt{P}l = L - l \tag{91}$$

and

$$l = \frac{L}{\sqrt{P}+1}. \tag{92}$$

From the table (Appendix C,) a corresponding value for the distance $l$ is obtained for each serial value of $P$, and the scale marked off accordingly. This table is based on a length $L$ of 100 units; for any other length, $aL$, the scale distance would be $al$, for

$$al = \frac{aL}{\sqrt{P}+1}. \tag{93}$$

The value of $I_c$ in terms of the unit $I_s$ is thus*

$$I_c = PI_s. \tag{94}$$

## THE PRACTICE OF THE PHOTOMETRY OF THE INCANDESCENT LAMP

**222. Adjusting the screen.** — Merely moving the screen slowly along the track until equilibrium of the two illuminations is apparently obtained, is a practice to be avoided. The eye is thus gradually led up to a condition that produces both fatigue and uncertainty; nor will it suffice to perform the operation more rapidly. The screen should be brought quickly to a position of approximate equilibrium of the illuminations, and then moved slowly both to the right and to the left, until a clearly observed difference of the illuminations is noted. These contrasts both sharpen and rest the eyesight, and the screen can then be moved to the balanced position with certainty. It is advisable to test the setting further by moving the screen to the right, say, until the slightest clearly perceived difference in the illuminations is found, noting the scale reading at this point and repeating the process to the left. Placing the screen

* See table Appendix C, for value of $P$.

now midway between the settings, if the illuminations are found to be in balance, this setting may be finally taken with confidence. This process of justification can only be readily applied with an equably divided scale, though with other scales the screen is to be brought to equilibrium through a slight movement in each direction.

To find the value* through which the illumination of the screen changes, suppose the screen is at a distance $l$ from a light of such intensity that the screen will receive $P$ units of illumination at the unit distance from it. The illumination $I$ at the distance $l$ is

$$I = \frac{P}{l^2}, \tag{95}$$

and the change of the illumination $\Delta I$, through a small movement $\Delta l$ in adjusting the screen is, the distance from the light now being $l + \Delta l$,

$$\Delta I = \frac{P}{l^2} \mp \frac{P}{(l \pm \Delta l)^2}. \tag{96}$$

These somewhat tedious methods are especially advised for those beginning photometrical work. Skill in such details is readily acquired, and in a short time settings can be rapidly made.

**223. The personal factor** originates in the part which the judgment plays, making the settings of the screen ultimately dependent upon a state of the optic nerve tract. The difficulties here are of the same character as those confronted when the standards of illumination were considered.

It is interesting to note some relevant experiments with the Bunsen screen made by E. L. Nichols.† These were devoted to comparisons between two incandescent lamps supplied by a storage battery, which, both by selection of the lamps and

* Philosophical Magazine, 36, 1893, page 122.

† Transactions American Institute of Electrical Engineers, 6, 1889, page 335.

their adjustment, were brought to practical equality of colour and intensity of illumination. The sight box seems to have been partitioned so that each eye was independently busied with its respective side of the screen. Series of observations were made independently, and under similar conditions, by two practised observers. These observations wandered from a certain established value by a mean of nearly 1.008, though in some cases the departure from the fixed value greatly exceeded this amount.

When one eye alone was brought to view both sides of the screen simultaneously, the departure was reduced to about 1.003, and it was indifferent whether the right or left eye was used.

As will be seen, this departure falls mainly to one side or other of the normal point, depending upon an idiosyncrasy of the observer. Some physicists have assumed this departure to be somewhat constant, both in amount and direction, and that it may be determined individually by the observer and applied as a correction factor to his observations.

Prior to this Liebenthal* had already investigated this factor with the added complication of the change in the screen itself. The mean value which he gives for a correction factor, in the observations he is discussing, is 1.002; but this varied from time to time with changes in the screen and in the state of the eye. Seemingly the quantitative discussion of the personal discrepancy of observations should be regarded as valuable for illustration rather than practice.

In case both eyes are used *independently* in the reading of a Bunsen screen, the mind is compelled to balance two judgments, arrived at from independent data; hence arises the uncertainty. In an observation the effect produced through the right eye may unconsciously preponderate, while in the very next observation, it may be the left eye; and this is further determined by the relative fatigue of the eyes. As a rule

* Elektrotech. Zeitschrift, 1888, page 102.

the colour sensitiveness differs in the individual in kind and degree between the eyes; and except in rare cases, where identical conditions confront each eye, binocular observations should be avoided. Even should the screen be so arranged that the eye may view both sides of it coördinately, the setting will be the result of a compromised judgment, and be uncertain to that extent. All this emphasizes the advisability of monocular readings, so that the personal factor may be more consistent.

With an apparatus such as the Lummer-Brodhun contrast optical screen, which is monocular, the discrepancy between individual observers may be considerable, and the personal factor seems to vary greatly from time to time.

It is clearly seen that a real difficulty in photometrical practice is here confronted.

Since the intensity and colour sensitiveness of the eye differs generally to some extent in the individual observer, but to a greater extent between different observers, in case the lights compared are of dissimilar colour the matter of personal drift in the settings will be more thoroughly emphasized, while it attains its least significance when lights of similar quality are compared. All this adds renewed emphasis to the assertion that photometry is only possible between similar qualities of light, compared under conditions of equal illumination of the sides of the screen.

**224. The fatigue of the eye.**—Through the continued action of daylight on the retina, the eye falls into a condition of minimum sensitiveness toward gradations of light, but recovery is rapid in the dark. The best photometrical results are obtained when an operator is assigned to the adjustment of the screen alone, leaving the manipulations of the lamps to another. The observer, on entering the photometer room, should remain in darkness for some minutes before attempting the reading of the screen, and should not keep his eyes continuously at work on the illuminated screen. After looking at this for a time, a coloured cast seems to flash over it, or it becomes bordered

with grayish light. These are complementary fatigue phenomena (page 17), and warn the operator to rest the eyes.

**225. Photometrical skill** is soon acquired by the operator, and through patience and careful training he will attain rapidity and accuracy in his work. Photometry is no exception in this regard, that results obtained by experienced observers are alone to be credited. Though the matter of the comparison of equal illuminations seems so simple an act that even an inexperienced eye should accomplish it with satisfactory accuracy, the causes leading to the personal factor make it far otherwise. Even with a considerable degree of experience the opportunities are numerous for errors of judgment and observation, and for omissions.

**226. The precautions in the use of flame standards** have already been pointed out (page 159), and are to be observed in case the photometry of the incandescent lamp begins with such a standard. One who has not attained considerable experimental skill with the use of flames can not expect to obtain any degree of accuracy with these standards. Unless one can bring time, patience, and a clear grasp of the subject to the task, it is advisable not to attempt the use of such standards, but to employ reliably calibrated incandescent lamps, thus greatly simplifying such measurements, and insuring a certain degree of accuracy from the first.

**227. Precautions in the use of incandescent lamp standards.** — Aside from the necessity for a close adjustment of the voltage and care to be exercised not to exceed the voltage for which lamps have been calibrated, there are a few significant minor details.

The bulbs must be thoroughly cleaned, preferably with a dilute solution of alcohol or ammonia. A standard lamp should be calibrated in a marked position, and replaced in the photometer in a like position. It is well not to calibrate a filament placed with its edge toward the screen, but rather to

place the plane of the filament at right angles with the photometrical axis.

Both lamps compared must be carefully centred with respect to this axis. This is readily accomplished by running the screen up to each lamp in turn, and adjusting the height so as to bring the optical centre of the filament to lie in the photometrical axis. The same observation applies to centring a standard flame.

The location of the optical axis of any given filament must be an act of judgment unless a meridian curve of the light distribution from the filament is at hand. In the plain horseshoe filament this lies just above the centre of its figure, while if the filament is looped, it is somewhat higher. This matter does not call for extreme accuracy.

Another observation will bear repeating in this connection: after a standard lamp has been obtained, two or more appropriate lamps should be selected and accurately compared with it, the lamps in each case being brought to a like quality of light with the standard. These are then to be placed aside to serve as checks for the standard.

Ordinarily the standard lamp should not be operated through a great range of incandescence, even should its constant be known, and the characteristic curves accurately determined; with such care the useful life of the lamp will be prolonged, and the quality of the light will be more nearly constant. Rather obtain a working range by the use of a number of lamps, of graded illuminating powers, or voltages, or a combination of these. Then the characteristics for these lamps over a limited range can be determined from one standard.

When a standard lamp is used on the photometer, it should be kept incandescent only when needed for a measurement; between such events the current should be turned off.

A small matter, but one that may assume importance, is that all labels should be attached before the lamp is photometered, even though they be small ones, and placed at the base next the cap.

**228. Spinning the lamp.** — This process may be applied to a lamp when photometered, provided a suitable rotator is available, otherwise it is apt to lead to erroneous results.

The *speed* at which the lamp is to be rotated will depend on certain conditions. A speed of two turns * per second has been prescribed, but this is too low, while a speed of three turns per second is also in current use. A speed of six turns per second, if the filament will bear it, is advised. The proper speed is not the same for all observers. This may be approximated in a given case by fastening two pieces of dark paper on the lamp bulb with rubber bands, the pieces to be placed opposite each other, and to be of such size as will sensibly diminish the light falling on the screen when they are facing it. If the lamp is now rotated until the light falling on the screen ceases to flicker, the critical speed has been found. But many filaments will not admit of such speed for any length of time. Looped filaments, especially if very long and slender, are difficult to spin; the filament best adapted for this process is the stiff horseshoe type.

The process can be applied to many filaments at moderate incandescence, but if this is increased until the temperature approaches the plastic state of the carbon, the filament will be markedly deformed. If the filament, too, is poorly centred, it will be apt to break at a high speed. The tangential force may cause a filament to spread until it touches and breaks the bulb. In any case the filament must be closely watched to note whether it is especially deformed by the spinning. If this is the case the spherical distribution of the light is correspondingly affected, and measurements made when the filament is in this condition will not give the spherical distribution of the light when the lamp is stationary. A standard lamp should never be spun.

If it is found that the filament under measurement bears the process of spinning, much time is saved in studying the space

* Report before the National Electric Light Association; Electrical Engineer, June 16, 1897, page 676.

distribution of its light, as only readings in inclination need be made, sparing all the tedious readings in azimuth; and should the conditions be entirely favourable, the values then found will more correctly integrate the mean intensity than when a mean is taken of the usual number of azimuth readings.

The light emitted by the incandescent lamp being so constant, however tedious the process of step by step measurement, the results are not in error from changes in the light strength to be measured.

**229. The calculation of the measurements.** — The photometer bar is commonly graduated from the left, and it is customary to place the standard lamp at this end. The measurements are calculated by the familiar formula applying to the balanced setting of the screen at a distance of $l$ units along the scale, the total distance between the lights compared being $L$ units. The illuminating power of the lamp photometered, $I_c$, in terms of the standard lamp $I_s$, is

$$I_c = \frac{(L-l)^2}{l^2} I_s. \qquad (88\ bis)$$

**230. The measurement of the spherical intensity.*** — For convenience the tip of the lamp and its base may be termed the north and south poles respectively.

The lamp is placed in the adjustable holder and brought into the standard position. Thirteen measurements are made by rotating the lamp horizontally, each interval being 30°, and the last measurement checking the first.

The mean of the thirteen readings will give the mean horizontal illuminating power.

Beginning again at 0° azimuth, thirteen readings are made in the prime meridian or vertical circle, the interval again being 30°, and the last reading checking the first.

* Report of Franklin Institute Tests on Incandescent Lamps, page 11; and Journal of the Franklin Institute, September, 1885. Also consult Liebenthal, Zeitschrift für Instrumentenkunde, 19, 1899, page 225.

It will be noticed that four readings, two being check readings, have been made at 0° azimuth. The mean of the four is taken as the *standard reading*, it being the value of the intensity, should the lamp be used as a standard.

Additional sets of thirteen readings each, the last reading checking the first one, are similarly made on each of the vertical circles through 45°, 90°, and 135° azimuth.

Sixty-five measurements in all are thus made, and in combining them for the mean spherical intensity, a note is taken of the repetitions, such as four measurements each at the north and south pole.

Neglecting the repetitions, which may also be omitted in part in the practice of the method, there remain thirty-eight points on the reference sphere, whose distribution is: —

| | Distributed Values |
|---|---|
| The mean of four measurements at the north pole of the lamp | 1 |
| Four measurements on each of the vertical circles through 0° and 90° azimuth at vertical circle readings of 60°, 120°, 240°, and 300° . . . . . . . . . . . . . . | 8 |
| Four measurements on each of the vertical circles through 0°, 45°, 90°, and 135° azimuth at vertical circle readings of 30°, 150°, 210°, and 330° . . . . . . . . . . . . | 16 |
| Twelve measurements 30° apart at the equator . . . | 12 |
| Four null values at the south pole of lamp . . . . | 1 |
| Total number of effective measurements . . . . | 38 |

The points thus laid off on the reference sphere are approximately equidistant, being somewhat closer together at the equator than at the poles.

**231. When the lamp is rotated,** readings are taken for each 15° or 30° in inclination, from 0° to 90°, and from 0° to 270°. These are integrated values for their corresponding parallels of latitude on the unit sphere.

The space distribution of light intensity will be a figure of revolution. A curve may be platted from these readings, from which the mean spherical intensity may be obtained (page 41)

by integrating the area of the curve with a planimeter, and equating the area to the mean circle.

**232. Observations on practical and laboratory apparatus.** — There has recently been a marked improvement of the class of photometers termed "portable." Formerly such an apparatus possessed questionable value as a measuring instrument. It was operated either with a candle or an oil lamp for the comparison light; and these, being so unreliable under the best laboratory conditions, as a matter of course proved practically worthless under the varied conditions of promiscuous testing. Since the perfection of the incandescent lamp and its demonstrated reliability as a working standard of light, the portable photometer has been improved until it is now a reasonably satisfactory instrument.

Such an apparatus has its peculiar requirements: it is commonly used by those having little laboratory experience, and a by no means comprehensive knowledge of the principles involved in the measurements they desire to accomplish. Their demand is for an apparatus reduced to the simplest possible elements with all its parts so adjusted that, by following certain plain directions, the results which they obtain will have a reasonable degree of certainty, and the apparatus shall prevent them from making the errors which might follow from deficient knowledge.

Those who demand "practical" apparatus which shall do their scientific thinking for them, are only too prone to inveigh against the refinements of laboratory apparatus and methods.

**233. The portable photometer for incandescent lamps.** — A description of the Queen portable photometer will be given as a representative of the advanced design of such apparatus. The photometer folds compactly and is carried in a convenient case. When arranged for testing (Fig. 56), the base forms a continuous bench, and lateral bellows extend from the sight box to the compared lights; and these in turn are covered

with light-proof hoods. The standard of light is a calibrated incandescent lamp. The sight box is of the conventional Bunsen type with reflecting mirrors; and the scale is marked off to be direct reading in candle units (page 37). The base on which the bench rests is in reality a switchboard which controls connections similar to those shown in Fig. 53, with the exception that a rheostat is used in each lamp circuit, permitting independent control of the voltage at each lamp. Either a voltmeter and ammeter, or a voltmeter and wattmeter, may be employed at pleasure, the instruments being switched successively from lamp to lamp. The operation of the apparatus should follow the precautions given on page 209. By covering the sight box with a light-proof cloth the photometer may be used in ordinary light.

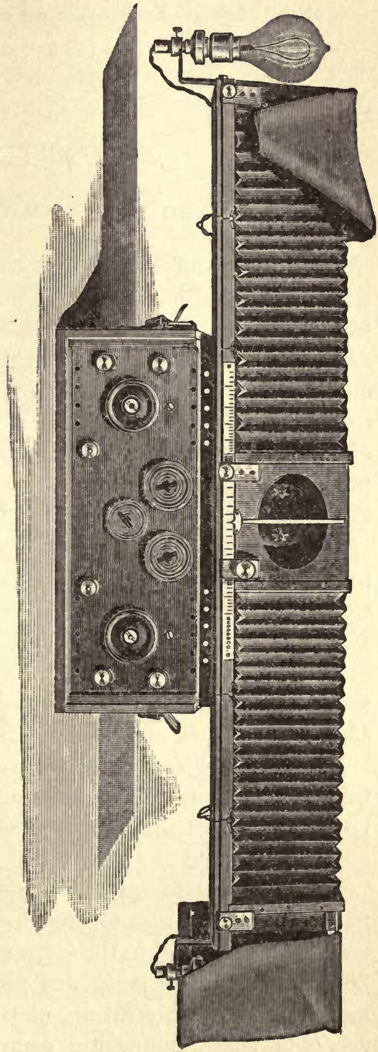

Fig. 56.

# CHAPTER VII

## THE ARC LAMP AND ITS PHOTOMETRY

**234.** The subject of the photometry of the arc lamp is beset with especial difficulties and uncertainties, should emphasis, by such an expression, be placed on the estimation of the light of the arc for purposes of continuous illumination, rather than on the specific measurement of its illuminating power. This distinction is insisted upon as a real one, for the measurement of the instantaneous illuminating power of the arc is susceptible of practically the same precision as the measurement of the illuminating power of the incandescent lamp.

The photometrical expression for the continuous illuminating power of the arc light has an applied value only when considered in connection with the behaviour and properties of the arc itself; otherwise, such expressions are misleading; and the distinction here insisted upon has been so generally overlooked that the photometry of the arc light has come to be regarded as both uncertain and valueless.

Early in the commercial development of the arc light certain designations were introduced, such as 1200 and 2000 candle power, based on the supposed maximum candle power, which apparently rated the illuminating power of the arc. These ratings were soon found to be misleading, and since the illuminating power was considered to be closely proportional to the energy transformed in the arc, a rating, such as 450 watts for the 2000 candle power lamp was proposed. Present practice is a modification of this rating, and in the absence of a generally accepted basis, lamps are commercially adjusted for certain current intensities, and the potential difference at which the

arc is operated is governed by the conditions of the grouping of lamps in the circuit, and the operation of the lamps with an open or enclosed arc.

In addition to a previous discussion of the physics of the arc (page 160) there are other details upon which its photometrical practice depends.

**235. The carbons.*** — A significant distinction amongst carbons is their degree of hardness, which may range from the gray metallic appearance of graphitic carbon, to the dull black colour of very soft and friable ones. A further distinction arises from the practice of coring them, which is applied to carbons of extreme or medium hardness, the core consisting of very soft carbon, a flux, and a binding material. A hard carbon consumes slowly, and burns with a lower efficiency, or requires more watts for a light unit than a softer carbon.

**236. The quality of the light.** — This is to a certain extent a function of the temperature of evaporation of the carbon (see page 163). Hard graphitic carbon has a higher boiling point than that which has a soft grain and is dull black in appearance. That quality of light which may be termed approximately normal white light, is emitted only by incandescent carbon of the softest variety when heated to its boiling point. The hardness of the carbon seems to raise its boiling point and increases the intensity of the higher light components, so that the light emitted has a bluish tinge.

**237. The emissivity of the carbon** for the arc light follows the same relations already pointed out in connection with the incandescent filament (page 172), or, in general, the increased hardness of the carbon lowers its emissivity for light radiations.

* L. B. Marks, Transactions American Institute of Electrical Engineers, 7, 1890, page 185; and W. M. S., Electrical Engineer, Oct. 3, 1894, and Electrical World, Feb. 23, 1895, page 223; also Blondel, L'Éclairage Électrique, March 13, 1897, page 500.

**238. The source of the luminosity of the arc.*** — The luminosity is principally a function of the incandescent state of the carbon. It is experimentally known that the positive carbon becomes heated to the temperature of ebullition, and the vapour from it passes to the negative tip of the arc. The positive tip or crater of the carbon, is highly incandescent, while the negative tip is only feebly so. Thus a very large percentage of the total illumination of the arc is emitted by the positive crater, the negative tip contributing but little, while the arc itself may be only faintly luminous, or brighter according to certain conditions. The arc, doubtless, consists principally of carbon vapour and to some extent of small particles of finely divided carbon carried over mechanically; and since incandescent gases are only feebly luminous, the arc can contribute but little to the total illumination except as it may contain particles of incandescent matter. Attempts to enrich the arc by introducing certain hydrocarbons † into it have not succeeded to any extent, for the hydrocarbons are not only decomposed, but the high temperature of the arc seems to vaporize the carbon, which in flames of lower temperature aggregates into small particles, and becoming incandescent, greatly increase the luminosity of the flame. The difficulties of a satisfactory study of the arc itself have so far proven insuperable.

When the arc is lengthened to any considerable extent, the carbon vapour in it probably becomes superheated and intensifies the violet radiations from the arc as a whole.

**239. The carbon points.** — After the carbon has been operating for some time the carbon tips attain shapes which are then maintained fairly uniform. If the arc is an open and continuous current one, the positive carbon becomes bluntly pointed like a truncated cone, with a well-defined crater at the place where the arc originates. If the carbon is homogeneous in its grain and quality, the points will be maintained symmetrical

* W. M. S., Electrical World, April 6, 1895, page 420.

† Journal Institute of Electrical Engineers, 1892, page 375.

to the axis of the carbon, though the edges of the crater will be rounded off. But should such a carbon be cored the crater will be deeper, with regular and sharper edges, and the symmetry of the cone will be better maintained. With carbons lacking in homogeneity of quality and structure, a soft core is a great aid toward their symmetrical consumption.

The negative carbon wears to a more decided point whose tapering sides are somewhat hollowed out. The influence of the negative carbon on the luminosity of the arc is so slight that there is no necessity for using an especially soft or a cored carbon, but such carbons are rather to be avoided since they are too soft under the impact of the arc stream, and wearing to a flat cone increase the unsteadiness of the arc and decrease the total illumination by a greater screening action.

When the arc is enclosed within the usual small glass chamber, the pointing of the carbons is greatly modified. The general tendency of the solid carbons, both positive and negative, is to wear off to blunt ends with slightly rounded edges. When a cored positive carbon is used the same tendency is seen, except in this case the centre is hollowed out by a more rapid consumption of the core. The tip of the negative carbon in either case is frequently somewhat irregular in outline, and may build up from the deposition of carbon vapour upon it.

**240. The position of the arc.** — Under normal conditions the arc stream passes between those points of the carbons which are least distant; but as the carbon wears away, the distance increases, and the arc is transferred to adjacent points, and in this manner travels about the circumference of the tips. This action seldom proceeds uniformly. The carbon may contain occluded gases which cause the arc to flame and rapidly change position. Hard particles and globules of foreign matter, such as silica, produce rapid shifting of the arc. These and other similar causes render the position of the arc inconstant. The illuminating power in any direction, and the total illumination, too, being a function of the energy transformed within it, are

constantly changing with more or less rapidity, for the consumption of the carbons lengthens the arc, and increases its potential difference, which further assumes a different value as the arc changes in position. As the distance between the carbons is adjusted by the regulation of the lamp, the position of the arc changes and its illumination is modified. These disturbances exist in the enclosed arc as well, but the changes take place much more slowly.

**241. The value of arc light photometry.** — It is these changes which cause the especial difficulties in the photometry of the arc light and its application to questions of illumination. By

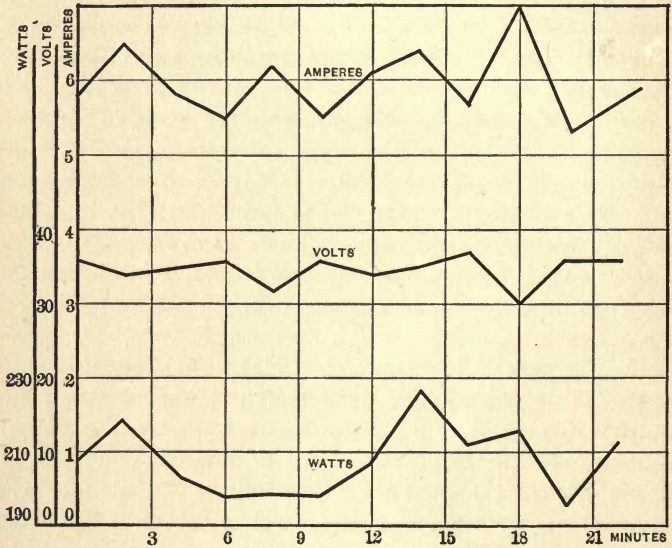


FIG. 57.

the adjustment of the lamp in feeding the carbons, the total light radiated, and its space distribution as well, necessarily change, and may even fall to a small fraction of their former values. (See Fig. 57.)

The distinction emphasized at the beginning of this discussion may now be enlarged upon. Except in cases of rapid adjustment of the lamp and the flaming of the carbons, or mechanical disturbances of the arc, its illuminating power may be measured with practically as great exactness as that of the incandescent lamp. The only real difficulty which the photometry of the arc opposes is the disparity in colour of light between itself and that of any secondary standard with which it may be compared. But it must be noted that these measurements yield only instantaneous values of the illuminating power for a certain radial direction from the arc. The fact that these instantaneous values are not maintained is the one which renders them of little service as ratings for the arc lamp. Not only the total illumination but its space distribution being inconstant, a photometrical rating of the arc lamp is in the main meaningless.

While the general practice of arc light photometry is not advisable, there are certain cases, other than those of pure research, in which it may prove valuable. If the conditions are carefully selected, and the measurements are made by skilled experimenters, photometry affords reliable information of the light-giving qualities of carbons and the absorption of globes and envelopes, and of the efficiency of reflectors. (Consult Appendix A.)

**242. The properties of the alternating current arc.** — The polarity of certain of the phenomena of the electric arc having been pointed out, the alternating current arc will, for purposes of this discussion, be considered as a sequence of arcs whose polarity is periodically reversed, and that each one in the series possesses all the properties of the constant polarity arc.* The pointing of the carbons is modified, and each tip in succession being the positive one, forms the characteristic crater. Either

* W. L. Puffer, Transactions American Institute of Electrical Engineers, 13, 1896, page 71.

one or both carbons may be cored, and the arc may be open or enclosed.

**243. The space distribution of the intensity of illumination.** — This has already been shown to vary with each change in the position of the arc, and the conformation of the crater, and the variation in quality of the carbon consumed. Were the arc perfectly constant in position and properties, the space distribution of its illumination would become an important function, and could be determined with great accuracy. The practical importance attaching to this quantity, is, however, a question rather of illumination than of photometry. For the latter the instantaneous intensities (especially the horizontal and the maximum) are the elements of importance, the mean spherical intensity having only a scientific value. While each measurement in a series from which the space distribution is calculated may be accurate in itself, the inconstant behaviour of the arc renders the mean obtained only an approximate, working one.

**244. The continuous current arc** exhibits a space distribution of illumination which is typically illustrated in Figure 58, in which the illuminating power of an arc supposed to be located at $O$ has been platted by polar coördinates. The maximum illuminating power is seen to occur at 40° inclination. The inclination and value of the maximum radius vector varies from time to time in any given arc, and between different arcs as well;* usually the inclination of the maximum radius vector lies between 40 and 50 degrees. The outline of such polar curves is roughly elliptical, and a number of investigators have deduced from its geometrical properties certain functions which enable approximate values of the illuminating power to be calculated for any desired inclination.† The horizontal illu-

* Consult Report of Franklin Institute Tests, V, 1885.

† Trotter, Journal Institute of Electrical Engineers, 1892, page 360; and Voit, Bericht der International Elektrisch Ausstellung zu München, 1882, pages 104 and 139; also Gerard, Centralblatt für Electrotechnik, January, 1890; and Palaz, La Lumière Électrique, 37, 1890, page 415.

minating intensity, which is most readily photometered, is about 20 per cent of the maximum value.

The contributions of the three elements producing the total illumination—the positive and negative carbon tips and the arc—may be approximately ascertained from such curves.

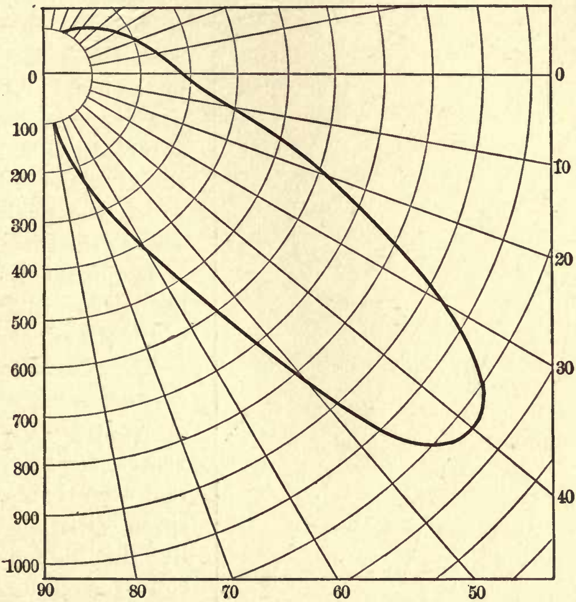


FIG. 58.

The interior of the positive crater is the principal source of light, and the small relative horizontal increment is due both to the arc stream and the negative tip. The positive carbon being the prime light source, the maximum intensity should occur in a radius normal to its plane, which if the crater is symmetrically located would be in the axis of the carbon. The illuminating power at any other point would vary from this as the cosine of its inclination (Lambert's law), according to Trotter.* That

* Reference cited.

the maximum intensity occurs not at 90° but at 45° to the horizontal, is due to the screening action of the negative tip. This seems well borne out by the polar curves of the arc. In Figure 59 Trotter has platted the polar curve of cosines with the polar curve of the arc.

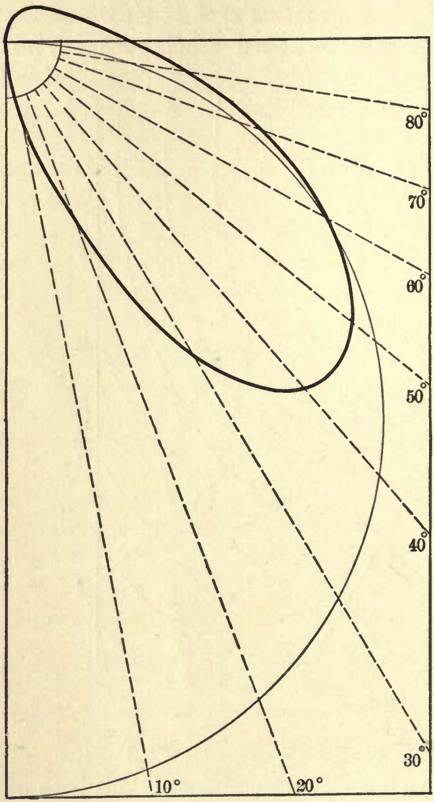


Fig. 59.

Polar curves of the arc are also valuable for studying the influence which the quality of the carbon, their shape and adjustment, has on the space distribution of the illumination.

*The alternating current arc* being a series of periodically reversed continuous current arcs, their virtual space distribution of illuminating power is closely given by duplicating the polar curve just described above the horizontal radius vector, as shown in Figure 60. At each alternation the positive tip becoming the negative tip for the following half period, cools down from the state of high incandescence of the positive crater, without in any case reaching the low temperature which it would attain with a continuous current, and this heightened incandescence of the negative tip very materi-

ally increases the horizontal intensity. This distinction is very strongly emphasized in the enclosed arc. (Compare Figures 58 and 61).

**245. The enclosed arc,*** whether supplied by a continuous or alternating current, shows a space distribution of illuminating power which is much affected by its enclosure.

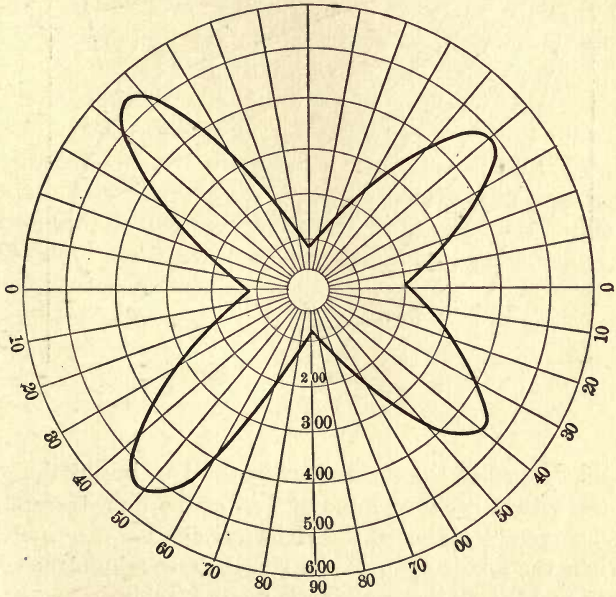


FIG. 60.

In the main the effect of an envelope tends toward a more uniform distribution of light. Both the character and the condition of the envelope have a modifying influence. If the glass

* L. B. Marks, Proceedings International Electrical Congress, 1893, page 387. L. B. Marks, Electrical World, Jan. 30, 1897, page 174; also Freedman, Transactions American Institute of Electrical Engineers, 14, 1897, page 425; and Matthews, Transactions American Institute of Electrical Engineers, 15, 1898, page 579.

has a matt surface, the total illumination is reduced and a fairly uniform space distribution results. Even with the purest carbons a gray coating forms on the interior of the chamber,

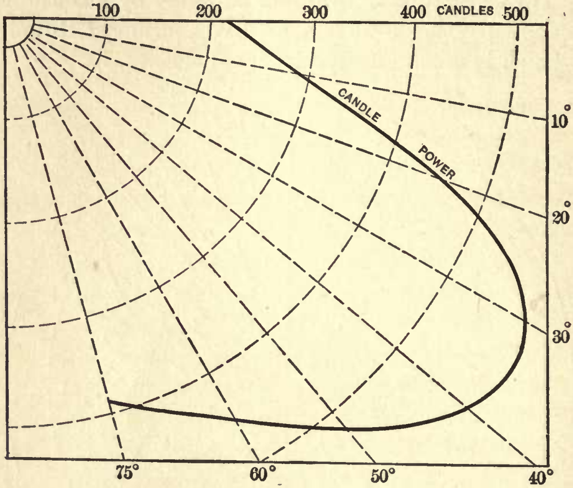


**Fig. 61.**

and this has much the same effect as the frosting of the glass, excepting that it changes the quality of the light transmitted, by selective absorption of the violet rays.

When the arc is open to the air, changes take place within it very rapidly, while enclosing it in an envelope greatly tends to steady it. The carbons wear away very slowly, and there is freedom from sudden cooling, with the result of a marked constancy in the distribution of light. The photometry of such arcs is not only more easily and rapidly performed, but the polar curves from such measurements have a greater practical value than in the case of the open arc. While the photometry of the open arc is not to be encouraged in general practice, except for purposes already pointed out, that of the enclosed arc bids fair to assume considerable practical importance.

**246. The mean spherical intensity of illumination** of the arc has already been alluded to as a quantity having rather scientific than practical interest. The intensity of the illumination in a definite direction is the only fact of value when considering the illumination from the arc light, the mean or average value for all directions is of no consequence. It is a useful device, however, when a comparison is made between several arcs or the same arc under varied conditions, involving a study of the total luminous radiation. Of its practical significance, Trotter * has said that "with a scientific but misguided regard for the truth, the candle power of arc lamps has been reduced to its mean spherical value by many authorities."

The quantity may be estimated from the intensity curves, (page 41), integrating them either mechanically or graphically, or by traversing the arc spherically. If the intensity curve is platted from the mean of a number of readings taken at sufficient time intervals to represent the average behaviour of the lamp, it may be assumed that these values will define the mean spherical distribution of the light, and that the spherical intensity distribution is a figure of revolution symmetrical about the axis of the carbons, and generated by the intensity curve.

Attempts have been made to obtain a function connecting the readily measurable horizontal and maximum intensities with the mean spherical candle power. It has already been shown that such a function can not exist in the nature of the case. Gerard † mentions an empirical one which was formerly largely used: that the mean hemispherical candle power, $S$, is related to the horizontal candle power, $H$, and the maximum candle power, $M$, by the expression,—

$$S = \frac{H}{2} + \frac{M}{4}. \tag{97}$$

* Journal Institute of Electrical Engineers, 1892, page 375.

† M. Gerard, "Candle Power of Arc Lamps," Centralblatt für Elektrotechnik, January, 1890.

**247. The efficiency of the arc lamp*** may be variously stated according to the meaning placed on the term. As a purely physical statement the radiant efficiency of the arc is the ratio between the luminous energy radiated and the total energy transformed in the arc; a quantity which has also been called the optical efficiency. The mean hemispherical efficiency of the enclosed arc with the continuous current is stated by Marks † to be 8.4 per cent; while that of the open arc is about 10 per cent.

## THE PRACTICE OF ARC LIGHT PHOTOMETRY

**248. The comparison light.** — In the previous discussion of standard and reference lights, the constancy of the light and the accuracy of reproduction were the primary considerations, though attention was called to the quality of the illumination; but in the photometry of the arc light the colour of the light is of the first importance.

Though such devices as the Lummer-Brodhun contrast optical screen and the flicker photometer yield good results in special cases, the general photometrical comparison of lights which differ to any extent in colour, has been seen to be difficult and more or less uncertain. Spectrophotometry affords an accurate means for comparing the intensities of definite colour constituents of the light, but such data give little information concerning the illuminating properties of the light. There remains the criterion for the accurate photometry of arc lights that comparisons be made only between equally lighted and similarly coloured fields.

The incandescent lamp is the one standard whose quality of light may be made to approach closely to that of the arc. The

* "The Efficiency of the Arc Lamp," H. Nakano, Transactions American Institute of Electrical Engineers, 6, 1889, page 308. Also, "The Efficiency of Light Sources," E. L. Nichols, Transactions American Institute of Electrical Engineers, 8, 1891, page 214.

† Proceedings International Electrical Congress, 1893, page 390.

quality of the arc light may vary from slightly yellowish white, through clear white to a bluish white, which idiosyncrasies of tint may be closely imitated by varying the voltage applied to the incandescent lamp. But these considerations finally resolve themselves into a comparison with the adopted primary light standard in order that the arc may be evaluated in terms of the primary unit. This is the most pronounced of the many difficulties incident to the photometry of the arc light. In the present stage of the development of arc light photometry, this light must be ultimately compared with the amyl acetate flame, or the illuminating power of a bluish white light must be expressed in terms of a distinctly reddish flame. The question, being ultimately a physiological one, no function is known, — and from the results of repeated experimental attempts it appears to be impossible of attainment, — which shall exactly connect the illuminating powers of differently coloured lights. The adoption of an especial standard of illuminating power for arc lights whose quality of light shall be the same as that of the arc itself has been advocated, but against this is urged the valid objection of the undue multiplication of standards and units.

**249. The incandescent lamp standard.** — The only plan available to the photometrician is to arrive at a working incandescent lamp standard, by a series of differentiations, beginning with the amyl acetate flame and varying the colour of the compared light slightly in each case. This result is unsatisfactory and can not lead to accurate statement. Apparently no light is sufficiently defined when it is stated to yield certain units of illuminating power, without at the same time specifying the quality of the light. If illumination is taken to mean the extent to which it enables objects to be clearly defined, then in this limited sense the illuminating power of the arc light may be expressed in amyl acetate units.

Two methods are open to the photometrician: to secure a reliably calibrated incandescent lamp from some authoritative

laboratory;* or to accomplish the calibration of the incandescent lamp directly from the primary standard.

**250. The calibration of the incandescent lamp.** — For this purpose the flicker photometer or the Lummer-Brodhun optical screen are to be preferred, though a skilled photometrician may perform the calibration satisfactorily with a Bunsen screen. In any case, the first comparison will be between the amyl acetate flame and the selected incandescent lamp. This should be brought to yield a light slightly whiter than the amyl acetate flame. After a satisfactory value for this incandescent lamp has been found, a second incandescent lamp is in turn compared with it, the voltage of the first lamp being maintained at the same value used in the first comparison; while the second lamp is burned yet brighter than the first one. By repeating this process between the same or different lamps and increasing the intensity of incandescence at each comparison, the desired tint is at length reached and the intensity of illumination is in a measure expressed by this step-up process in terms of the amyl acetate standard.

When the incandescence of a lamp is raised to such a degree that the light emitted is bluish white, the temperature is so high that the carbon is near the plastic state, and slowly volatilizes, and the lamp will not continue to emit a constant illuminating power for any length of time. Before using a calibrated lamp in practice, it is well to standardize several lamps against it, and reserve these to check the working standard from time to time.

A calibration curve may be obtained for the working lamp between its illuminating power and the voltage (page 183) which will be of assistance when it becomes necessary to adjust its incandescence to accord with the different tint of the arc light. Attention is again called to the necessity for using a

* Consult the Electrical World and Engineer, editorial, July 8, 1899, page 39; also Doane, Transactions American Institute of Electrical Engineers, 1899.

sensitive and accurately calibrated voltmeter with the standard incandescent lamp and for supplying it with a current from a storage battery.

The size of the incandescent lamp to employ as a working standard depends on the dimensions of the photometrical train; in order to shorten the distance between the screen and the arc light it may be necessary to use a high power lamp. In any case very strong illumination of the screen is to be avoided, as it renders the eye less sensitive. The fact, too, that the lamp is burned in excess of its normal rating must be taken into account when selecting a lamp for a certain working power of the standard.

**251. Mirrors** are a useful adjunct to a photometer train. They require to be kept scrupulously clean and should have the surface free from scratches. They need to be calibrated for position, for a certain portion of the incident light is absorbed, and some light is irregularly reflected. The quality of the light is also affected by selective absorption, a property of the mirror which varies in intensity with the inclination of the incident light; while some experimenters have failed to find the action appreciable.*

If the mirror is to be used in an angular position which will require continued adjustment to the position of the radiant, it should be provided with an index quadrant, and be calibrated for changes of the angular position. Frequently mirrors are used at a fixed angle of about 45°; and the loss of light can be determined for this set position.

Incandescent lamps are preferable for such calibration work and this may be performed on the usual photometer bench. The lamps are first compared directly, one being mounted on some radial device, which will enable a fixed distance between the lamps to be maintained when the mirror is introduced at

* Matthews, Transactions American Institute of Electrical Engineers, 15, 1898, page 583.

any reflecting angle.* Then comparisons are made with the mirror set at the desired angle.

If the illuminating power of one lamp in terms of the other, without the use of the mirror, is $b_1$, and with the mirror is $b_2$, the coefficient of diminution of the light $c$ will have a value

$$c = \frac{b_2}{b_1}. \tag{98}$$

A convenient correction factor $a$ is obtained by making

$$a \equiv \frac{1}{c} = \frac{b_1}{b_2}. \tag{99}$$

When the mirror is used with an arc lamp, the illuminating power of the arc after reflection, $I_2$ is too small, owing to loss of light by the mirror; its value $I_1$, which would have been obtained had its light passed directly to the screen is then

$$I_1 = aI_2, \tag{100}$$

which is the working equation for such corrections.

An elaborately mounted mirror is not a necessity; one may be improvised with a piece of heavy plate glass, at most six inches square, whose surface is truly plane. If the mirror is to be used in a fixed position after adjustment to the desired reflecting angle, a socket joint is the best attachment for the mounting. Should it be desired to make successive angular adjustments, the mirror should be movable about a horizontal axis, which should lie in the optical axis of the photometer bench.

**252. The suspension of the arc lamp** for the measurement of the illuminating power will depend upon the photometrical method to be followed. If merely the horizontal intensity is to be photometered for various points in azimuth, the lamp will require only a simple suspension to bring the arc itself into

* Matthews, ref. cit., page 581.

the photometrical axis, with some device for turning it in azimuth and indicating its angular position. Obviously the photometer can not be made to traverse the arc spherically, but this is indirectly accomplished by using reflecting mirrors.

By one method, which has been frequently used,* the arc is traversed by a mirror attached to a short arm, movable about an axis bolted to the frame of the arc lamp. This is a tedious method, and necessitates numerous adjustments of the mirror.

A preferable method is to swing the arc lamp from an upper vertex of a jointed rectangular frame, the opposite side of which is rigidly fastened in the vertical plane through the photometrical axis, the mirror being mounted at the diagonal vertex, and with its centre in the photometrical axis and moved by the lower member of the frame, the lamp being so suspended that the arc lies in the axis of the member and at a distance of about four feet from the mirror. An index finger may be attached to the frame for indicating its inclination. The arc must move in a plane perpendicular to the photometrical axis, and preferably in the same plane which contains the centre of the mirror, an adjustment readily effected when the frame is horizontal.

Various other suspensions will doubtless suggest themselves, yet it is advisable to adopt a method which will maintain a fixed distance between the arc and mirror.

**253. The arrangement of the photometer train.**—The photometer train will include the bench and its accessories, the mirror, the suspension frame and the arc, together with any light-diminishing devices. Since all arrangements involve essentially similar photometrical principles, a typical case is

* Franklin Institute Tests, ref. cit.; also Journal Institute of Electrical Engineers, 1892, page 360; Elektrotech. Zeitschrift, 1883, page 444, and 1887, page 357.

illustrative: this is shown in outline in Figure 62. The photometer bench *AB* may have a working length of either 100 inches, 2 metres, or even less with a light-reducing device. Both the standard light *S* and the photometer screen *C* are operated in the usual positions.

The photometer bench may be placed in a separate room, or enclosed in a light-proof canopy. The light from the arc is admitted through a boxed opening approximately the size of the optical screen, and placed directly in the photometrical axis, the opening being through a chamber whose sides are sufficiently separated to prevent the admission of extraneous light.

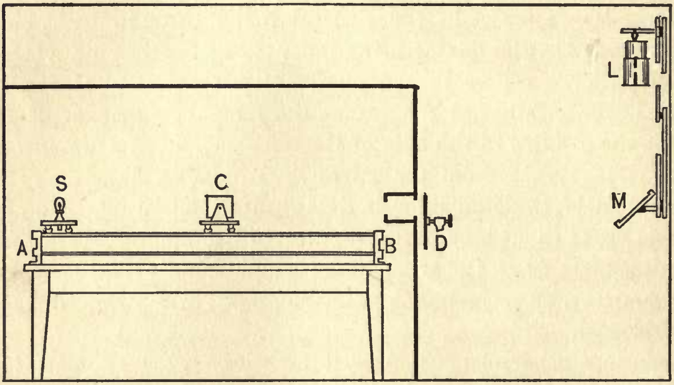


FIG. 62.

A revolving sector-disk is placed at *D*, just beyond the opening The reflecting mirror is at *M*, and the arc to be photometered is located at *L*.

The distance between *L* and *S*, measured with reference to the centre of the mirror, is taken at 5 metres, or, if the dimensions are in English measure, for ready calculation it may be made 20 feet. It is to be understood that these dimensions are merely suggestive, and in some cases they may be exceeded to an advantage, though a shorter length than 5 metres is not advisable.

A rotating sector-disk will prove a useful adjunct to the photometer train, though it is not a necessity, provided the distance between the standard light and the arc can be made sufficiently large. The diameter of the disk may be 8 or 10 inches; the relative area of the openings, the speed at which it should be operated, and the coefficient of its diminution of the light have already been discussed (page 24).

**254. The photometer adjustments.** — The maximum sensitiveness of the adjustment of the screen occurs for a given interval between the lights, when a balance is obtained midway of the illuminations compared; and while the general tendency in photometrical measurements should be toward this condition, yet, on account of the great inequalities in the lights compared, the condition operates only as a tendency. It may be approached, however, by employing high illuminating power in the standard light, or diminishing the light of the arc, and especially by a combination of these expedients. The sensitiveness in the setting of the screen is also increased by lengthening the distance between the compared lights.

Specific directions can not be given governing the illuminating power of the standard light and the various dimensional details of the photometrical train; these must be determined for individual cases, and can readily be decided upon after making preliminary calculations.

The brilliant illumination of any photometrical screen is to be avoided, for in weak light the eye is more sensitive to changes in the illumination. Similarly, the employment of a sectored disk is advisable for reducing the intensity of the arc light; the fatigue of the eye is less in weaker light.

**255. In illustration** of some of these details, the distance between the arc and the standard lights will be taken at 500 centimetres. Suppose the screen is at a distance of $l$ centimetres from the standard, then to decrease the light falling upon it by one-hundredth part, the distance between the two

must be increased $x$ centimetres, and applying the photometrical law of inverse squares,

$$\frac{100}{99}=\frac{(l+x)^2}{l^2}. \tag{101}$$

Two initial positions of the screen may be taken, giving $l$ the values of 15 and 90 centimetres, and the corresponding values of $x$ are found to be 0.075 and 0.45 centimetres. These values express, in a manner, the relative sensitiveness of the adjustment of the screen. The range of movement, when the screen is at a distance of 90 centimetres, for a visible change of the light falling on the screen, is so much greater than in the former case that it leads both to greater ease of work and exactness, for a slight error in the estimation of the distance $l$ will be of less consequence, the greater it is made.

For the sake of simplicity, the light falling on the screen from one source only has been considered. In a rigid investigation of the adjustment the contrast difference of the one-hundredth part would be taken between the light on the screen from each source, which would lead to complicated mathematical expressions. At a screen distance of only 15 centimetres the above analysis is not appreciably in error.

Denoting the illuminating power of the arc by $I_a$, and of the standard by $I_s$, for a distance between these of 500 centimetres,

$$I_a=\frac{(500-l)^2}{l^2}I_s. \tag{102}$$

If $I_s$ be one light unit, and $l$ 15 centimetres,

$$I'_a=1045 \text{ light units,}$$

and if $I_s$ has an intensity of 50 light units, and $l$ be 90 centimetres, then

$$I''_a=1038 \text{ light units.}$$

This clearly shows that, for the photometry of a given luminous intensity of the arc light, a high-power comparison light,

when no light-reducing device is used, leads to increased sensitiveness in the setting of the screen, and diminishes the influence of the errors of adjustment and measurement.

**256. Sundry details.**—In addition to the general directions for the preparation of the photometer room (page 198), if the arc lamp be suspended in an outer room, its walls must be as carefully blackened as those of the room in which the photometer bench is placed. All portions of the photometer train must be given a dull black finish, and if the arc lamp has bright metallic parts, these must be covered with some non-reflecting material.

Two operators will be necessary for such tests, one to adjust the position of the arc, and a second to make the adjustment of the screen. The latter operator should avoid looking at the arc light or the reflecting mirror, and not attempt an adjustment of the screen until the eyes have become rested from the external light.

**257. The calculations of the illuminating power** are made after the general photometrical equation on page 207.

Denoting the distance between the lights by $L$, and between the screen and the light standard by $l$, the illuminating power of the arc by $I_a$, and the standard by $I_s$, then, as before, from equation 88,

$$I_a = \frac{(L-l)^2}{l^2} I_s, \tag{103}$$

provided no light-reducing device has been used between the arc and the screen. If a rotating sector-disk has been employed, whose correction factor is $a$, then the previous equation reads,

$$I'_a = a\frac{(L-l)^2}{l^2} I_s. \tag{104}$$

**258. The measurement of the intensity of powerful light sources.**—The facilities of the ordinary photometer room are not

adapted for measuring the illuminating power of light sources, whose intensity greatly exceeds that of arc lights in common use. This is especially the case with search lights.

The optical bench available in the photometer room, if it is equipped with a Lummer-Brodhun optical screen, may be adapted for this work by interposing one or more opal glass diffusing and absorbing screens between the sight box and the light source. The details for such practice will be found clearly outlined in the discussion of the Weber photometer (pages 82–85). This apparatus, however, is preferable for such work, on account of its flexibility and portability.

# APPENDIX

*A.* THE ABSORPTION OF LIGHT BY GLOBES AND THE ACTION OF REFLECTORS.

*B.* RECENT INVESTIGATIONS OF LAMBERT'S LAW FOR THE REFLECTION OF LIGHT.

*C.* TABLE OF RATIOS FOR A 100-PART PHOTOMETER BAR.

## *A*. THE ABSORPTION OF LIGHT BY GLOBES AND THE ACTION OF REFLECTORS

THOUGH the technical importance of this subject is immediately apparent, it has received little precise investigation. The great variety of globes and reflectors in use, and the prevailing conditions under which they are employed, are scarcely amenable to classification and precise treatment. These matters are details for a thorough science of illumination, if it is a possibility of the future that such a science will be developed.

Several investigations of the absorption of light by globes have been published;* and one of the most practical of these studies has recently been accomplished by Williamson and Klinck, who have experimented on the globes and reflectors in common use with gas and electric lights.† The present discussion is largely abstracted from their paper before the Franklin Institute.

Globes and reflectors modify the intensity, light quality, and intrinsic brightness of a light source in several ways: (*a*) the radiations falling on the surface of the globe or reflector suffer partial absorption, and are lessened in intensity; (*b*) radiations are brought into a desired direction by reflection or refraction; (*c*) radiations are changed in quality by selective absorption in the material of the globe.

* W. E. Sumpner, Philosophical Magazine, 35, 1893, page 51. Th. Stort, Elektrotech. Zeitschrift, No. 32, 1895, page 500; given in abstract in Electrical Review (London), July 10, 1896, page 37; and in Electrical World, 26, 1895, page 265.

† "A Photometrical Comparison of Illuminating Globes," R. B. Williamson and J. H. Klinck; a paper read before the Electrical Section of the Franklin Institute, March 21, 1899, and published in its Journal, Vol. 149, 1900, page 66.

The source of light employed in their experiments was a Welsbach burner, and the action of the globe or reflector was studied by means of a Bunsen photometer. The change in the quality of the light by selective absorption was not studied.

The action of such globes as affect the quality of the light, notably opal glass, can only be accurately stated when their influence on the quality of the light is taken into account; and the strictly scientific study of the present subject would entail complete spectrophotometrical measurements; but when it is remembered that there are no optical standards that are followed in the manufacture of the globes, and that any commercial variety varies widely in its action on the transmitted light, it is apparent that such measurements would have little technical value. Any data, therefore, presented on the behaviour of commercial globes toward light are to be considered as indicative rather than conclusive.

The areas included by the curves shown in the illustrations were determined in the square-inch unit from the original curves, and the mean spherical candle power was calculated by the methods already explained (page 41). In the application of these curves to the distribution of light from an incandescent lamp, it must be remembered that the test light was a gas flame, and that the curve of light distribution from the bare burner greatly differs from the curve of distribution from an incandescent lamp (Fig. 50). Care must also be exercised to consider the incandescent lamp and the globe or reflector to be placed in relative positions equivalent to those which were used in these tests.

Two similar Welsbach mantles were used: one was maintained in a fixed position as a standard, and its illuminating power was repeatedly checked; the second mantle was mounted on a traversing arm, the burner being kept vertical in all angular positions of the arm. A reflecting mirror, set at 45°, was attached to the axis of the bar, which was adjusted to lie in the photometrical axis of the bench. The globes and reflectors were tested on this comparison light.

I. Holophane globe of clear glass intended for the horizontal distribution of light, Figure 63.

CURVE A, WITHOUT GLOBE

| | |
|---|---|
| Area above the horizontal axis . . . | 12.58 |
| Area below the horizontal axis . . . | 11.15 |

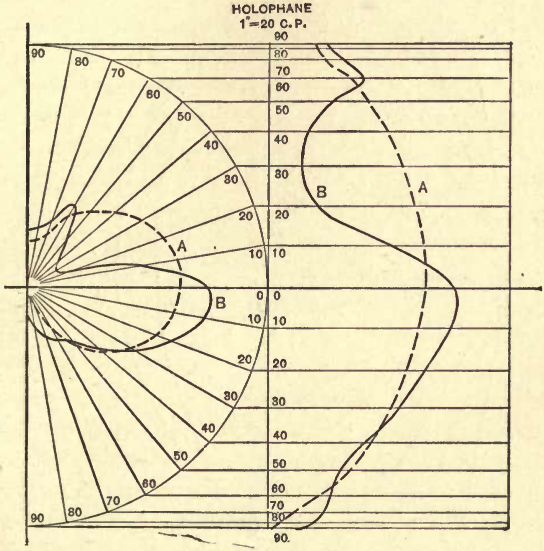


FIG. 63.

CURVE B, WITH HOLOPHANE GLOBE

| | |
|---|---|
| Area above the horizontal axis . . . | 7.92 |
| Area below the horizontal axis . . . | 12.72 |
| Efficiency . . . . . . . . . | 87% |
| Mean spherical candle power, A . . . | 46.46 |
| Mean spherical candle power, B . . . | 41.28 |

The holophane globe was pear-shaped and ribbed vertically on the interior, and horizontally on the exterior, surface. The inner ribs were all similar in shape with a sinusoidal section, and the horizontal ones varied with their location.

II. Ground glass globe with wide flutings, Figure 64.

### Curve A, without Globe

| | |
|---|---|
| Area above the horizontal axis . . . | 12.40 |
| Area below the horizontal axis . . . | 10.78 |

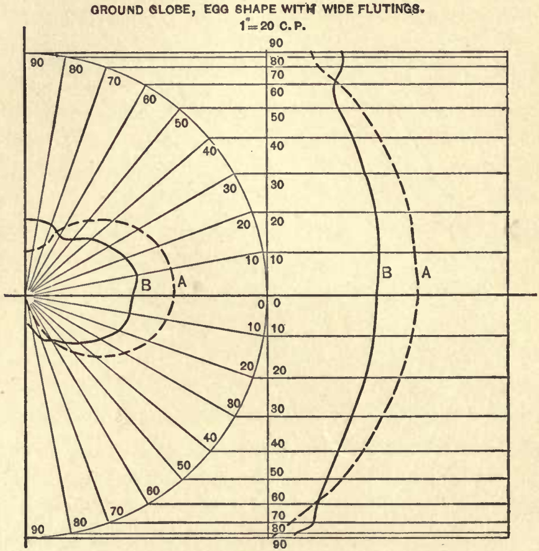


Fig. 64.

### Curve B, with Ground Glass Globe

| | |
|---|---|
| Area above the horizontal axis . . . | 9.96 |
| Area below the horizontal axis . . . | 8.44 |
| Efficiency . . . . . . . . | 79.3% |
| Mean spherical candle power, A . . . | 46.36 |
| Mean spherical candle power, B . . . | 36.80 |

The globe was egg-shaped with wide shallow flutings on both the exterior and interior surfaces. Beyond diminishing the radial intensity of the light, the flux above the horizontal plane was increased.

III. Plain opal glass globe, Figure 65.

CURVE A, WITHOUT GLOBE

| | |
|---|---|
| Area above the horizontal axis . . . | 12.40 |
| Area below the horizontal axis . . . | 10.78 |

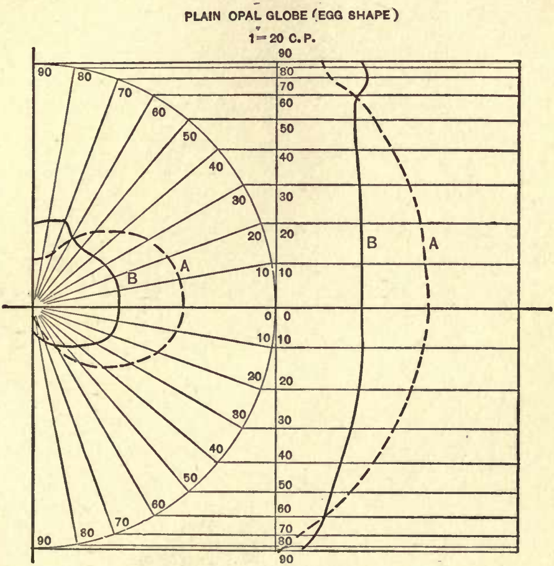


FIG. 65.

CURVE B, WITH PLAIN OPAL GLASS GLOBE

| | |
|---|---|
| Area above the horizontal axis . . . | 8.68 |
| Area below the horizontal axis . . . | 7.21 |
| Efficiency . . . . . . . . | 68.5% |
| Mean spherical candle power, A . . . | 46.36 |
| Mean spherical candle power, B . . . | 31.78 |

This globe was also egg-shaped with both the exterior and the interior surfaces plane. There is a marked upward displacement of the intensity curve as well as large absorption of light, with consequent low efficiency.

IV. Slightly opalescent globe, Figure 66.

CURVE A, WITHOUT GLOBE

| | |
|---|---|
| Area above the horizontal axis . . . | 11.00 |
| Area below the horizontal axis . . . | 9.60 |

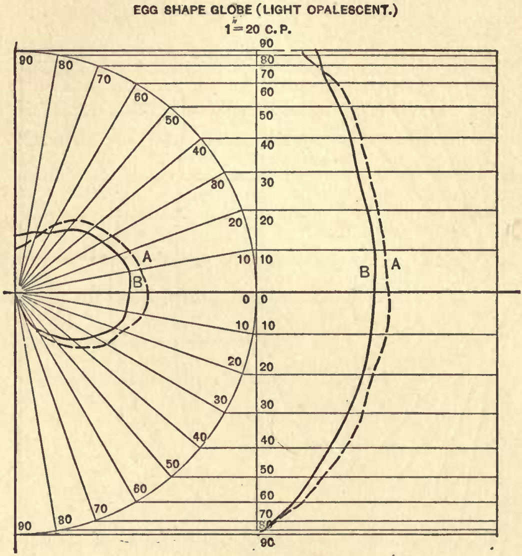


FIG. 66.

CURVE B, WITH OPALESCENT GLOBE

| | |
|---|---|
| Area above the horizontal axis . . . | 10.12 |
| Area below the horizontal axis . . . | 8.48 |
| Efficiency . . . . . . . . . | 90.2% |
| Mean spherical candle power, A . . . | 41.2 |
| Mean spherical candle power, B . . . | 37.2 |

This, too, was an egg-shaped globe with shallow flutings arranged spirally on one surface and vertically on the other. The general light distribution is but slightly affected, and the absorption is very low.

V. Flat opal glass reflector, fluted, Figure 67.

CURVE A, WITHOUT REFLECTOR

| | |
|---|---|
| Area above the horizontal axis . . . | 12.58 |
| Area below the horizontal axis . . . | 11.15 |

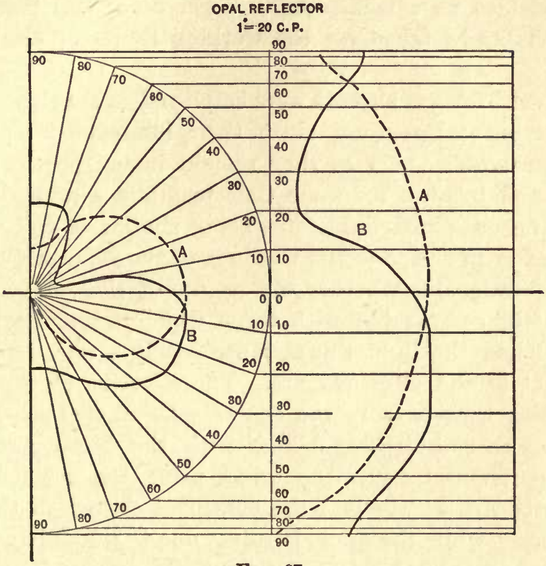


FIG. 67.

CURVE B, WITH OPAL GLASS REFLECTOR

| | |
|---|---|
| Area above the horizontal axis . . . | 6.41 |
| Area below the horizontal axis . . . | 14.20 |
| Efficiency . . . . . . . . . | 86.8% |
| Mean spherical candle power, A . . . | 46.46 |
| Mean spherical candle power, B . . . | 41.22 |

The reflector was practically flat with deep radial flutings. The increase in the intensity beneath the horizontal is clearly shown; while the marked loop at the top of the curve is due to light which passed through the large opening in the centre of the reflector.

A plain, clear glass globe did not alter the distribution of the light, and showed an efficiency of 94.5 per cent. A clear glass globe having the ordinary pear-shaped form, and made with narrow vertical flutings, gave an efficiency of 86.6 per cent; while another, similarly shaped, but having narrow ribs inside, yielded an efficiency of 91.5 per cent; and these data may probably be taken for the working limits of clear glass globes.

The Welsbach gas burners were employed as the light source, for experimental reasons, since their luminous intensity is fairly constant so long as they remain intact, provided they are allowed to burn for some time to attain a normal condition. The compared lights too, being similar in colour, they gave greater precision to the readings of the Bunsen screen.

It is questionable whether the results of these experiments are strictly comparable with those which would have been obtained had the light source more nearly agreed in quality with that of the electrical arc. The selective absorption in the globes, especially in the opalescent and opal ones, would doubtless be considerably higher with the bluer arc light. The experimental difficulties when using the arc itself, for such tests, are very great; the continual change in the light distribution while the arc is burning, due to the shifting position of the arc, and the variation of its potential difference, are obstacles which have never been satisfactorily overcome.

Investigations of the light-absorbing power of globes with the arc light have been attempted, however, notably by Stort* and Shepardson.† The arc lamp employed by Stort was operated with a current intensity of 10 amperes; and by the use of a lens and screen, the length of the arc was maintained at 2 millimetres; the positive carbon had a diameter of 17, and the negative one of 10 millimetres. The values which he obtained are probably too small, and rather underestimate the screening action of the globes. They are: —

* Th. Stort, reference cited.

† G. D. Shepardson, Electrical World; 23, 1894, page 287.

| | Luminous Intensity in Candles | | | |
|---|---|---|---|---|
| | Maximum intensity | Lower mean hemispherical intensity | Total mean spherical intensity | Loss by absorption. Per cent. |
| Naked light . . . | 1,161 | 635 | 362 | 0 |
| Clear globes . . . | 1,165 | 606 | 336 | 6 |
| Frosted globes . . | 654 | 494 | 320 | 11 |

Shepardson found that the distribution of the light was especially disturbed by the action of an opal or white glass globe. Using various globes and comparing the intensity of the light at the angle of maximum intensity for the bare arc, he found that a clear glass globe reduced the intensity to 82 per cent, a ground glass globe to 47 per cent, and an opal glass globe to 33 per cent of the value of the illumination from the bare arc.

Such results naturally follow from the diffusing action of the globes on the light given from the arc, which is much greater than their absorption of the light.

The photometrical measurements which tests of this character involve are necessarily tedious, and they require that the source of light shall remain constant throughout the tests. Doubtless an incandescent lamp operated at an abnormally high voltage would prove a more satisfactory source of light than any hitherto employed, and the quality of the light could be made to approximate closely to that of the arc light.

## *B.* RECENT INVESTIGATION OF LAMBERT'S LAW FOR THE REFLECTION OF LIGHT

Lambert's law of the cosines has been simply phrased in the text (page 33) to meet the requirements of the discussions and applications which involve this principle. A more extended discussion will be attempted in this section.

The law deals with secondary sources of illumination (page 28), and is a fundamental one for all reflecting screens. In order to derive a general expression for the law, consider two diffusing surfaces, $S_1$ and $S_2$, separated by a distance of $d$ units; these surfaces are not necessarily planes, but may have any geometrical character. An infinitesimal area $ds_1$ is taken on the surface $S_1$, and similarly $ds_2$ on $S_2$; and being so small, they will be regarded as plane surfaces. The surface $S_1$ is illuminated by a light source, and by diffusion emits light to the second surface $S_2$; the light thus is emitted from $S_1$ and is incident upon $S_2$. The path of this light makes an angle of emission $\epsilon$, with the normal to the surface element $ds_1$, and an angle of incidence $\iota$, with the normal to the surface element $ds_2$. The intrinsic brightness (page 32) of the emitting surface $S_1$, measured normally, will be taken at $B$ units, and the quantity of light $q$, which finally falls on the surface element $ds_2$, is

$$q = \frac{B}{d_2} ds_1 \, ds_2 \cos \epsilon \cos \iota, \tag{105}$$

which is the most general expression for Lambert's law.

Or, one surface, $S_1$, alone may be considered, which receives from a light source an illumination whose intensity (page 30) measured normally is $I$ units. The illumination is incident upon the surface element $ds_1$, at an angle $\iota$, and the diffused light $q$ at an angle of emission $\epsilon$ will be

$$q = I \, ds_1 \cos \epsilon \cos \iota. \tag{106}$$

The phenomenon of the diffuse reflection of light is entirely dependent upon the character of the reflecting surface. If this contains plane surface elements, whose size is a magnitude which is large in comparison with the dimensions of the incident light wave, a certain amount of regular or specular reflection (page 8) will occur, associated with an amount of diffused reflection; and the regular reflection obeys the law of the

equality of the angles of incidence and reflection, while Lambert's law would apply to the diffused portion of the reflected light. The smaller the grain of the surface becomes, the more closely will Lambert's law express the relations between the incident and the emitted light, providing this law precisely defines the phenomenon.

The efforts of later investigators of the validity of this law have been especially directed toward the production of a sufficiently fine-grained surface to insure complete diffusion of the light and eliminate all regular reflection. A surface of this nature is properly called a "matt" surface. In the last analysis all light waves are reflected regularly, however small the grain of the surface; and the distinction between diffuse and specular reflection is one wholly of direction. In the case of specular reflection a considerable quantity of light is reflected in a particular direction; when diffuse reflection occurs, the quantities of light specularly reflected from the surface elements are very small, for the planes of the elements will likely be so disposed with reference to each other that their normals will radiate in all directions with considerable uniformity; the result would be that no measurable quantity of reflected light would have a defined direction.

Wright* attempted to produce a matt surface by compressing powders in steel moulds into coherent blocks under pressures of 4 to 20 tons. He found no evidence of normal reflection occurring from the surfaces thus prepared, and he considered them properly matt surfaces. Amongst other materials compressed and tested, he used carbonate of magnesium and plaster of Paris; and he observed that the size of the particles was not changed by the compression to which they were subjected. The fact that he could detect no polarization of the light upon reflection was taken as the evidence that no normal reflec-

* H. R. Wright, "Photometry of the Diffuse Reflexion of Light on Matt Surfaces," *Philosophical Magazine*, February, 1900, page 199; the paper gives an excellent summary of the investigations of Lambert's law.

tion of the light had taken place. A matt surface properly defined is one which entirely diffuses the light reflected from it without polarization, or specular reflection. Specular reflection detected from surfaces supposed to be matt ones, would indicate that the reflecting areas of the particles were large relative to the dimensions of the light waves, or that a peculiarly orderly arrangement of exceedingly minute surface planes had occurred. As the latter is improbable, the absence of specularly reflected, or polarized light is apparently sufficient evidence of the matt character of the surface.

The conclusions at which Wright arrived from his experiments were: —

1. "Common light is not polarized by diffuse reflection.

2. "The intensity of the light diffusely reflected under the angles $+\epsilon$ and $-\epsilon$ is the same, or it is independent of the azimuth. There is no specular reflection.

3. "The law of emission by constant incidence is independent of colour, or the coefficient of diffusion is independent of the wave length in the case of particles of the given size.

4. "A law for the intensity of reflected scattered light can not be symmetrical in reference to the angles $\iota$ and $\epsilon$.

5. "The intensity of the diffuse reflected light with the angle $\epsilon$ constant and with varying angles of incidence $\iota$, is not proportional to the cosine $\iota$, as Lambert assumes.

6. "The intensity of the diffuse reflected light with the angle $\iota$ constant and the angle $\epsilon$ varying, is proportional to the cosine $\epsilon$, or *Lambert's law of emanation is strictly correct for absolutely matt surfaces without any exception.*

7. "The so-called 'law of the cosine' ($q = \Gamma_2 ds \cdot \cos\iota \cos\epsilon$) is not true in consequence of the deviations of the law of the cosine $\iota$. The deviations range between 4.6 per cent and 10 per cent."

From considerations of the geometrical character of truly matt surfaces, it is probable that the quantity of light emitted is not strictly a function of the cosine $\epsilon$.

These considerations are of great importance in their relation to diffusing plates employed in such photometers as the Lummer-Brodhun and the Leonhard Weber; and there is need of marked improvement in the surfaces of the plates usually provided. They also emphasize the necessity for the symmetrical adjustment of the Lummer-Brodhun sight box regarding the angles of the incident and emitted rays.

## *C.* TABLE OF RATIOS FOR A 100-PART PHOTOMETER BAR*

The formula for the calculation of the intensity of a compared light by use of this table of ratios, is:

$$I_c = PI_s,$$

in which $I_c$ is the light intensity sought, and $I_s$ that of the standard light, while the value of the ratio $P$, is taken from the table, corresponding to the observed scale reading.

Thus, if the screen is set at a distance of 40.6 units from the standard light, the ratio for this scale reading is 2.14, and if $I_s$ has a value of 14.5 light units,

$$I_c = 2.14 \times 14.5$$

$$= 31.03 \text{ light units.}$$

* W. L. Smith, Technology Quarterly, 1896, page 60.

| Ratio | Scale | Ratio | Scale | Ratio | Scale | Ratio | Scale | Ratio | Scale |
|---|---|---|---|---|---|---|---|---|---|
| .10 | 75.97 | .47 | 59.33 | .84 | 52.18 | 1.21 | 47.62 | 1.58 | 44.31 |
| .11 | 75.09 | .48 | 59.07 | .85 | 52.03 | 1.22 | 47.51 | 1.59 | 44.23 |
| .12 | 74.27 | .49 | 58.82 | .86 | 51.88 | 1.23 | 47.41 | 1.60 | 44.15 |
| .13 | 73.50 | .50 | 58.57 | .87 | 51.74 | 1.24 | 47.31 | 1.61 | 44.08 |
| .14 | 72.77 | .51 | 58.34 | .88 | 51.60 | 1.25 | 47.21 | 1.62 | 44.00 |
| .15 | 72.08 | .52 | 58.10 | .89 | 51.46 | 1.26 | 47.11 | 1.63 | 43.92 |
| .16 | 71.43 | .53 | 57.87 | .90 | 51.32 | 1.27 | 47.01 | 1.64 | 43.85 |
| .17 | 70.81 | .54 | 57.64 | .91 | 51.18 | 1.28 | 46.92 | 1.65 | 43.77 |
| .18 | 70.21 | .55 | 57.42 | .92 | 51.04 | 1.29 | 46.82 | 1.66 | 43.70 |
| .19 | 69.64 | .56 | 57.20 | .93 | 50.90 | 1.30 | 46.72 | 1.67 | 43.62 |
| .20 | 69.10 | .57 | 56.98 | .94 | 50.77 | 1.31 | 46.63 | 1.68 | 43.55 |
| .21 | 68.58 | .58 | 56.77 | .95 | 50.64 | 1.32 | 46.54 | 1.69 | 43.48 |
| .22 | 68.07 | .59 | 56.56 | .96 | 50.51 | 1.33 | 46.44 | 1.70 | 43.41 |
| .23 | 67.58 | .60 | 56.35 | .97 | 50.38 | 1.34 | 46.35 | 1.71 | 43.33 |
| .24 | 67.12 | .61 | 56.15 | .98 | 50.25 | 1.35 | 46.26 | 1.72 | 43.26 |
| .25 | 66.66 | .62 | 55.95 | .99 | 50.12 | 1.36 | 46.16 | 1.73 | 43.19 |
| .26 | 66.23 | .63 | 55.75 | 1.00 | 50.00 | 1.37 | 46.07 | 1.74 | 43.12 |
| .27 | 65.81 | .64 | 55.55 | 1.01 | 49.88 | 1.38 | 45.98 | 1.75 | 43.05 |
| .28 | 65.40 | .65 | 55.36 | 1.02 | 49.76 | 1.39 | 45.89 | 1.76 | 42.98 |
| .29 | 65.00 | .66 | 55.17 | 1.03 | 49.63 | 1.40 | 45.80 | 1.77 | 42.91 |
| .30 | 64.61 | .67 | 54.98 | 1.04 | 49.51 | 1.41 | 45.72 | 1.78 | 42.84 |
| .31 | 64.24 | .68 | 54.80 | 1.05 | 49.39 | 1.42 | 45.63 | 1.79 | 42.77 |
| .32 | 63.87 | .69 | 54.62 | 1.06 | 49.27 | 1.43 | 45.54 | 1.80 | 42.70 |
| .33 | 63.51 | .70 | 54.44 | 1.07 | 49.15 | 1.44 | 45.45 | 1.81 | 42.64 |
| .34 | 63.17 | .71 | 54.27 | 1.08 | 49.04 | 1.45 | 45.37 | 1.82 | 42.57 |
| .35 | 62.83 | .72 | 54.10 | 1.09 | 48.93 | 1.46 | 45.28 | 1.83 | 42.50 |
| .36 | 62.50 | .73 | 53.93 | 1.10 | 48.81 | 1.47 | 45.20 | 1.84 | 42.44 |
| .37 | 62.18 | .74 | 53.76 | 1.11 | 48.70 | 1.48 | 45.12 | 1.85 | 42.37 |
| .38 | 61.86 | .75 | 53.59 | 1.12 | 48.59 | 1.49 | 45.03 | 1.86 | 42.30 |
| .39 | 61.55 | .76 | 53.42 | 1.13 | 48.48 | 1.50 | 44.95 | 1.87 | 42.24 |
| .40 | 61.25 | .77 | 53.26 | 1.14 | 48.36 | 1.51 | 44.87 | 1.88 | 42.18 |
| .41 | 60.97 | .78 | 53.10 | 1.15 | 48.25 | 1.52 | 44.79 | 1.89 | 42.11 |
| .42 | 60.68 | .79 | 52.94 | 1.16 | 48.14 | 1.53 | 44.71 | 1.90 | 42.04 |
| .43 | 60.39 | .80 | 52.78 | 1.17 | 48.04 | 1.54 | 44.62 | 1.91 | 41.98 |
| .44 | 60.12 | .81 | 52.63 | 1.18 | 47.93 | 1.55 | 44.54 | 1.92 | 41.92 |
| .45 | 59.85 | .82 | 52.48 | 1.19 | 47.83 | 1.56 | 44.47 | 1.93 | 41.85 |
| .46 | 59.58 | .83 | 52.33 | 1.20 | 47.72 | 1.57 | 44.39 | 1.94 | 41.79 |

| Ratio | Scale | Ratio | Scale | Ratio | Scale | Ratio | Scale | Ratio | Scale |
|---|---|---|---|---|---|---|---|---|---|
| 1.95 | 41.73 | 2.64 | 38.10 | 3.38 | 35.23 | 5.05 | 30.79 | 6.90 | 27.57 |
| 1.96 | 41.67 | 2.66 | 38.01 | 3.40 | 35.16 | 5.10 | 30.69 | 6.95 | 27.50 |
| 1.97 | 41.61 | 2.68 | 37.92 | 3.42 | 35.10 | 5.15 | 30.59 | 7.00 | 27.43 |
| 1.98 | 41.55 | 2.70 | 37.83 | 3.44 | 35.03 | 5.20 | 30.49 | 7.05 | 27.36 |
| 1.99 | 41.48 | 2.72 | 37.75 | 3.46 | 34.97 | 5.25 | 30.38 | 7.10 | 27.29 |
| 2.00 | 41.42 | 2.74 | 37.66 | 3.48 | 34.90 | 5.30 | 30.28 | 7.15 | 27.22 |
| 2.02 | 41.30 | 2.76 | 37.58 | 3.50 | 34.83 | 5.35 | 30.18 | 7.20 | 27.15 |
| 2.04 | 41.18 | 2.78 | 37.49 | 3.55 | 34.67 | 5.40 | 30.09 | 7.25 | 27.08 |
| 2.06 | 41.06 | 2.80 | 37.41 | 3.60 | 34.51 | 5.45 | 29.99 | 7.30 | 27.01 |
| 2.08 | 40.95 | 2.82 | 37.32 | 3.65 | 34.36 | 5.50 | 29.89 | 7.35 | 26.95 |
| 2.10 | 40.83 | 2.84 | 37.24 | 3.70 | 34.21 | 5.55 | 29.80 | 7.40 | 26.88 |
| 2.12 | 40.72 | 2.86 | 37.16 | 3.75 | 34.05 | 5.60 | 29.70 | 7.45 | 26.81 |
| 2.14 | 40.60 | 2.88 | 37.08 | 3.80 | 33.90 | 5.65 | 29.61 | 7.50 | 26.75 |
| 2.16 | 40.49 | 2.90 | 37.00 | 3.85 | 33.76 | 5.70 | 29.52 | 7.55 | 26.69 |
| 2.18 | 40.38 | 2.92 | 36.92 | 3.90 | 33.62 | 5.75 | 29.43 | 7.60 | 26.62 |
| 2.20 | 40.27 | 2.94 | 36.84 | 3.95 | 33.47 | 5.80 | 29.34 | 7.65 | 26.55 |
| 2.22 | 40.16 | 2.96 | 36.76 | 4.00 | 33.33 | 5.85 | 29.25 | 7.70 | 26.49 |
| 2.24 | 40.05 | 2.98 | 36.68 | 4.05 | 33.19 | 5.90 | 29.16 | 7.75 | 26.43 |
| 2.26 | 39.95 | 3.00 | 36.60 | 4.10 | 33.06 | 5.95 | 29.07 | 7.80 | 26.37 |
| 2.28 | 39.84 | 3.02 | 36.53 | 4.15 | 32.92 | 6.00 | 28.99 | 7.85 | 26.30 |
| 2.30 | 39.74 | 3.04 | 36.45 | 4.20 | 32.79 | 6.05 | 28.90 | 7.90 | 26.24 |
| 2.32 | 39.63 | 3.06 | 36.37 | 4.25 | 32.66 | 6.10 | 28.82 | 7.95 | 26.18 |
| 2.34 | 39.53 | 3.08 | 36.30 | 4.30 | 32.54 | 6.15 | 28.74 | 8.00 | 26.12 |
| 2.36 | 39.43 | 3.10 | 36.23 | 4.35 | 32.41 | 6.20 | 28.66 | 8.05 | 26.06 |
| 2.38 | 39.33 | 3.12 | 36.15 | 4.40 | 32.28 | 6.25 | 28.58 | 8.10 | 26.00 |
| 2.40 | 39.23 | 3.14 | 36.08 | 4.45 | 32.16 | 6.30 | 28.49 | 8.15 | 25.94 |
| 2.42 | 39.13 | 3.16 | 36.01 | 4.50 | 32.04 | 6.35 | 28.41 | 8.20 | 25.88 |
| 2.44 | 39.03 | 3.18 | 35.93 | 4.55 | 31.92 | 6.40 | 28.33 | 8.25 | 25.82 |
| 2.46 | 38.93 | 3.20 | 35.86 | 4.60 | 31.80 | 6.45 | 28.25 | 8.30 | 25.77 |
| 2.48 | 38.84 | 3.22 | 35.79 | 4.65 | 31.68 | 6.50 | 28.17 | 8.35 | 25.71 |
| 2.50 | 38.75 | 3.24 | 35.72 | 4.70 | 31.57 | 6.55 | 28.09 | 8.40 | 25.65 |
| 2.52 | 38.65 | 3.26 | 35.64 | 4.75 | 31.45 | 6.60 | 28.01 | 8.45 | 25.60 |
| 2.54 | 38.55 | 3.28 | 35.57 | 4.80 | 31.34 | 6.65 | 27.94 | 8.50 | 25.54 |
| 2.56 | 38.46 | 3.30 | 35.50 | 4.85 | 31.22 | 6.70 | 27.87 | 8.55 | 25.48 |
| 2.58 | 38.37 | 3.32 | 35.44 | 4.90 | 31.12 | 6.75 | 27.79 | 8.60 | 25.43 |
| 2.60 | 38.28 | 3.34 | 35.37 | 4.95 | 31.01 | 6.80 | 27.72 | 8.65 | 25.37 |
| 2.62 | 38.19 | 3.36 | 35.30 | 5.00 | 30.90 | 6.85 | 27.64 | 8.70 | 25.32 |

| Ratio | Scale | Ratio | Scale | Ratio | Scale | Ratio | Scale | Ratio | Scale |
|---|---|---|---|---|---|---|---|---|---|
| 8.75 | 25.27 | 9.65 | 24.35 | 12.75 | 21.88 | 17.25 | 19.39 | 23.50 | 17.10 |
| 8.80 | 25.21 | 9.70 | 24.30 | 13.00 | 21.71 | 17.50 | 19.28 | 24.00 | 16.95 |
| 8.85 | 25.16 | 9.75 | 24.26 | 13.25 | 21.55 | 17.75 | 19.18 | 24.50 | 16.81 |
| 8.90 | 25.10 | 9.80 | 24.21 | 13.50 | 21.39 | 18.00 | 19.07 | 25.00 | 16.67 |
| 8.95 | 25.05 | 9.85 | 24.17 | 13.75 | 21.24 | 18.25 | 18.97 | 25.50 | 16.53 |
| 9.00 | 25.00 | 9.90 | 24.12 | 14.00 | 21.09 | 18.50 | 18.86 | 26.00 | 16.40 |
| 9.05 | 24.95 | 9.95 | 24.07 | 14.25 | 20.94 | 18.75 | 18.76 | 26.50 | 16.27 |
| 9.10 | 24.90 | 10.00 | 24.03 | 14.50 | 20.80 | 19.00 | 18.66 | 27.00 | 16.14 |
| 9.15 | 24.85 | 10.25 | 23.80 | 14.75 | 20.66 | 19.25 | 18.56 | 27.50 | 16.01 |
| 9.20 | 24.79 | 10.50 | 23.58 | 15.00 | 20.52 | 19.50 | 18.46 | 28.00 | 15.89 |
| 9.25 | 24.74 | 10.75 | 23.37 | 15.25 | 20.39 | 19.75 | 18.37 | 28.50 | 15.78 |
| 9.30 | 24.69 | 11.00 | 23.17 | 15.50 | 20.26 | 20.00 | 18.28 | 29.00 | 15.66 |
| 9.35 | 24.64 | 11.25 | 22.97 | 15.75 | 20.13 | 20.50 | 18.09 | 29.50 | 15.55 |
| 9.40 | 24.60 | 11.50 | 22.77 | 16.00 | 20.00 | 21.00 | 17.91 | 30.00 | 15.45 |
| 9.45 | 24.55 | 11.75 | 22.57 | 16.25 | 19.88 | 21.50 | 17.74 | | |
| 9.50 | 24.50 | 12.00 | 22.40 | 16.50 | 19.75 | 22.00 | 17.57 | | |
| 9.55 | 24.45 | 12.25 | 22.23 | 16.75 | 19.63 | 22.50 | 17.41 | | |
| 9.60 | 24.40 | 12.50 | 22.05 | 17.00 | 19.51 | 23.00 | 17.25 | | |

| Ratio | Scale | Ratio | Scale | Ratio | Scale | Ratio | Scale | Ratio | Scale |
|---|---|---|---|---|---|---|---|---|---|
| 31 | 15.23 | 43 | 13.23 | 60 | 11.43 | 90 | 9.54 | 150 | 7.55 |
| 32 | 15.02 | 44 | 13.10 | 62 | 11.27 | 95 | 9.31 | 155 | 7.44 |
| 33 | 14.83 | 45 | 12.97 | 64 | 11.11 | 100 | 9.09 | 160 | 7.33 |
| 34 | 14.64 | 46 | 12.85 | 66 | 10.96 | 105 | 8.89 | 165 | 7.22 |
| 35 | 14.46 | 47 | 12.73 | 68 | 10.82 | 110 | 8.70 | 170 | 7.12 |
| 36 | 14.28 | 48 | 12.61 | 70 | 10.67 | 115 | 8.53 | 175 | 7.03 |
| 37 | 14.12 | 49 | 12.50 | 72 | 10.54 | 120 | 8.36 | 180 | 6.94 |
| 38 | 13.96 | 50 | 12.39 | 74 | 10.41 | 125 | 8.21 | 185 | 6.85 |
| 39 | 13.80 | 52 | 12.18 | 76 | 10.29 | 130 | 8.06 | 190 | 6.77 |
| 40 | 13.65 | 54 | 11.98 | 78 | 10.17 | 135 | 7.92 | 195 | 6.68 |
| 41 | 13.51 | 56 | 11.79 | 80 | 10.06 | 140 | 7.79 | 200 | 6.60 |
| 42 | 13.37 | 58 | 11.61 | 85 | 9.79 | 145 | 7.67 | | |

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THE NUMBERS REFER TO THE PAGE

F



G



H



I

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K



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M



N



O



P

# INDEX TO NAMES

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